

**TOWARD DESIGNING A SUSTAINABLE WATERSHED
RECLAMATION STRATEGY**

A Thesis Submitted to the
College of Graduate Studies and Research
In Partial Fulfillment of the Requirements For the
Degree of Doctor of Philosophy

In the
Department of Civil and Geological Engineering
University of Saskatchewan
Saskatoon

By
Nader Keshta

© Copyright Nader Keshta, September, 2010. All rights reserved.

Permission to use

In presenting this thesis in partial fulfillment of the requirements for a postgraduate degree from the University of Saskatchewan, I agree that the libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by my supervisor, and in his absence, by the Head of the Civil and Geological Engineering or the Dean of the College of Engineering. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to myself and to the University of Saskatchewan for any scholarly use which may be made of any material in this thesis.

Requests for permission to copy or to make other use of material in this thesis in whole or part should be addressed to:

Head of the Department of Civil and Geological Engineering
University of Saskatchewan
Saskatoon, Saskatchewan
Canada, S7N 5A9

Abstract

Oil sands mining results in significant disturbances to natural ecosystems when soil and overburden materials are removed and stockpiled to provide access to mined materials. The mining process must be followed by land reclamation, whereby disturbed landscapes are recovered with the intent to replicate the performance of natural watersheds. Modeling hydrological processes in reclaimed landscapes is essential to assess the hydrological performance of the reclamation strategies as well as their evolution over time, and requires a reliable and continuous source of input data. In pursuit of simulating the various hydrological processes, such as soil moisture and actual evapotranspiration, a lumped generic system dynamics watershed (GSDW) model has been developed. The validity of the proposed model has been assessed in terms of its capacity to reproduce the hydrological behaviour of both reconstructed and natural watersheds.

Data availability is a major challenge that constrains not only the type of models used but also their predictive ability and accuracy. This study evaluates the utility of precipitation and temperature data from the North American Regional Reanalysis (NARR) versus conventional platform data (e.g., meteorological station) for the hydrological modeling. Results indicate NARR data is a suitable alternative to local weather station data for simulating soil moisture patterns and evapotranspiration fluxes despite the high complexity involved in simulating such processes. Initially, the calibrated GSDW model was used along with available historical meteorological records, from both Environment Canada and NARR, to estimate the maximum soil moisture

deficit and annual evapotranspiration fluxes. A probabilistic framework was adopted, and frequency curves of the maximum annual moisture deficit values were consequently constructed and used to assess the probability that various reconstructed and natural watersheds would provide the desired moisture demands. The study shows a tendency for the reconstructed watersheds to provide less moisture for evapotranspiration than natural systems. The probabilistic framework could be implemented to integrate information gained from mature natural watersheds (e.g., the natural system canopy) and transfer the results to newly reconstructed systems.

Finally, this study provided some insight into the sensitivity of soil moisture patterns and evapotranspiration to possible changes in the projected precipitation and air temperature in the 21st century. Climate scenarios were generated using daily, statistically downscaled precipitation and air temperature outputs from global climate models (CGCM3), under A2 and B1 emission scenarios, to simulate the corresponding soil moisture and evapotranspiration using the GSDW model. Study results suggest a decrease in the maximum annual moisture deficit will occur due to the expected increase in annual precipitation and air temperature patterns, whereas actual evapotranspiration and runoff are more likely to increase.

Acknowledgements

I would like to express my gratitude and appreciation to my supervisor, Dr. Amin Elshorbagy, for his invaluable guidance and support throughout my Ph.D. program. His critical appraisal and suggestions have been priceless at every stage of this research.

I would like to extend my acknowledgement to my advisory committee members Dr. S. L. Barbour, Dr. B. C. Si, and Dr. S. K. Carey for their valuable suggestions and feedback. The time and support of my advisory committee chair, Dr. G. Putz is greatly acknowledged. I would also like to acknowledge Dr. Alan Barr from the BOREAS and BERMS Organizations, for providing the required data in this research work. Also, I would like to express my deep appreciation and gratitude to Dr. B. M. Watson for offering his assistance.

I want to take this opportunity to thank my colleagues at the Centre for Advanced Numerical Simulation (CANSIM), my friends, and staff at the Department of Civil and Geological Engineering, for making my stay at the University of Saskatchewan a memorable one.

Last but not the least; I am extremely grateful to my wife, parents, brother and sister for their unwavering guidance and support throughout my Ph.D. program, and to my children for providing me with the motivation and determination to reach this point.

Table of Contents

Permission to use	i
Abstract.....	ii
Acknowledgements.....	iv
Table of Contents.....	v
List of Tables	x
List of Figures	xii
List of Abbreviations	xvi
Chapter 1 - Introduction	1
1.1 Background.....	1
1.2 Area of interest.....	2
1.3 Problem recognition.....	3
1.4 Research Objectives.....	5
1.5 Scope of the research program.....	6
1.6 Synopsis of the thesis.....	10
1.7 References.....	12
Chapter 2 - A Generic System Dynamics Model for Simulating and Evaluating the Hydrological Performance of Reconstructed Watersheds	15
Contribution of the PhD candidate.....	15
Contribution of this chapter to the overall study.....	15
2.1 Abstract.....	17
2.2 Introduction.....	18
2.3 Modeling of Reconstructed Watersheds	21
2.4 GSDW Model Development and Formulation	22
2.4.1 Canopy storage.....	26
2.4.2 Surface water storage.....	29
2.4.3 Soil water storage.....	29
2.4.4 Evapotranspiration module	33
2.4.5 Interflow component.....	34
2.4.6 Overland flow component.....	36
2.5 Case Studies	37

2.5.1 Reconstructed watersheds	37
2.5.2 Natural Watersheds	39
2.6 Results and Analysis	41
2.6.1 SWAT model	44
2.6.2 Simulation results of the GSDW model.....	46
2.7 Discussion	59
2.8 Conclusions.....	62
2.9 Acknowledgements.....	64
2.10 References.....	64
Chapter 3 - Comparative Probabilistic Assessment of the Hydrological Performance of Reconstructed and Natural Watersheds.....	72
Contribution of the PhD candidate.....	72
Contribution of this chapter to the overall study.....	72
3.1 Abstract.....	74
3.2 Introduction.....	75
3.3 Case Studies	79
3.3.1 Reconstructed Watersheds	79
3.3.2 Natural Watersheds	80
3.4 Hydrological Modeling.....	82
3.4.1 Model Description	82
3.4.2 Methodology	85
3.5 Results and Discussions	89
3.5.1 Hydrological Performance Assessment for Reconstructed Inclined Watersheds 89	
3.5.2 Hydrological Performance Assessment of Reconstructed and Natural Horizontal Watersheds.....	93
3.5.3 Hydrological Performance Assessment of Vegetation Alternatives.....	95
3.5.4 Hydrological Performance Assessment of Actual Evapotranspiration (AET) Fluxes for Different Sites.....	98
3.6 Conclusions.....	101
3.7 Acknowledgements.....	102

3.8	References.....	103
-----	-----------------	-----

Chapter 4 - Utilizing North American Regional Reanalysis for Modeling Soil

Moisture and Evapotranspiration in Reconstructed Watersheds 108

	Contribution of the PhD candidate.....	108
	Contribution of this chapter to the overall study.....	108
4.1	Abstract.....	110
4.2	Introduction.....	111
4.3	Methods.....	115
	4.3.1 Study Areas and Onsite Data Collection	115
	4.3.2 Model Description	117
	4.3.3 Hydrologic Modeling.....	118
	4.3.4 Hydrologic Modeling.....	121
4.4	Results and Discussion	122
	4.4.1 Data acquisition and corrections.....	122
	4.4.2 Evaluation of the NARR Reanalysis Data	124
	4.4.3 GSDW model simulation results	129
	4.4.3.1 D3 cover hydrologic performance	129
	4.4.3.2 SWSS watershed hydrologic performance	133
	4.4.4 Long term probabilistic assessment of the hydrological performance of reconstructed watersheds	139
4.5	Conclusions.....	142
4.6	Acknowledgements.....	144
4.7	References.....	144

Chapter 5 - Impacts of Climate Change on Soil Moisture and Evapotranspiration in Reconstructed Watersheds 150

	Contribution of the PhD candidate.....	150
	Contribution of this chapter to the overall study.....	150
5.1	Abstract.....	152
5.2	Introduction.....	152
5.3	Global Circulation Models (GCMs)	155
5.4	Impacts of climate change on the hydrological processes	157

5.5	Study areas	160
5.6	Methodology	161
5.6.1	Statistical downscaling technique and climate scenarios.....	162
5.6.1.1	Coupled Global Climate Model (CGCM's) data	162
5.6.1.2	Statistical Downscaling Model (SDSM).....	163
5.7	Hydrological modeling	164
5.8	Long term probabilistic assessment of the hydrological performance of reconstructed watersheds	165
5.9	Results and Discussion	167
5.9.1	Downscaling results during the baseline period	167
5.9.2	Downscaled GCM outputs corresponding to future climate scenarios.....	167
5.9.3	Long term probabilistic assessment of moisture deficit	170
5.9.4	Hydrological performance assessment based on actual evapotranspiration (AET) fluxes	175
5.10	Conclusions.....	179
5.11	Acknowledgements.....	180
5.12	References.....	181
	Chapter 6 - Conclusions	187
6.1	Summary of the Thesis	187
6.2	Research Contribution	192
6.3	Possible Research Extension.....	193
6.4	Study Limitations.....	195
	Appendix. A	196
A.1	Natural watersheds.....	196
A.2.1	Equipments and limitations.....	200
a)	Equipments	200
b)	Data Limitations	202
A.2	Reconstructed Watersheds	204
A.2.1	Equipments and limitations.....	206
a)	Equipments	206
b)	Data corrections and limitations	208

A.3 References:.....	210
A.4 Reconstructed watersheds photos	213

List of Tables

Table 2-1 Calibration parameter values for the developed GSDW model	43
Table 2-2 Performance statistics of the GSDW and the SWAT models regarding soil moisture.....	48
Table 2-3 Performance statistics of the GSDW model regarding daily AET flux	57
Table 2-4 Annual water balance components for the validation years.....	58
Table 4-1 Calibration parameter values for the GSDW models.....	120
Table 4-2 Percentiles of daily precipitation (mm/day) for the D3 cover (onsite station) and NARR datasets.	125
Table 4-3 Root mean squared errors (RMSE) and correlation coefficients (R) for NARR precipitation and temperature, respectively, compared to the D3 onsite station.	126
Table 4-4 Descriptive statistical properties of precipitation for the NARR and D3 station datasets.	128
Table 4-5 Performance statistics of the GSDW model regarding soil moisture during the validation period.	131
Table 5-1 Percentiles of daily precipitation (mm/day) and temperature (°C) at Fort McMurray station and SDSM-downscaled CGCM3 scenarios.	168
Table 5-2 Descriptive statistical properties of precipitation (mm/day) and temperature (°C) at Fort McMurray station and SDSM-downscaled scenarios.	169
Table A.1 Description of the study sites (old jack pine, and old aspen), Saskatchewan, Canada.....	199
Table A.2 Climate variables measured in the natural watersheds.	200

Table A.3 Description of the reconstructed study sites.	209
--	-----

List of Figures

Figure 1-1 Framework of the research program for developing a sustainable reclamation strategy (SRS) (modified after Julta, 2006; Parasuraman, 2007).	7
Figure 2-1 A schematic diagram of the GSDW model structure.....	24
Figure 2-2 Causal-loop diagram of the developed GSDW model.....	25
Figure 2-3 Simulated and observed moisture dynamics in the D3 cover for validation year 2006 using both SWAT and GSDW models; (a) peat layer; (b) till layer.	46
Figure 2-4 Simulated and observed moisture in the SWSS watershed; (a) Till layer calibration (2006); (b) Tailings sand layer calibration (2006); (c) Till layer validation (2005); (d) Tailings sand layer validation (2005).	52
Figure 2-5 Simulated and observed moisture in the SBH watershed; (a) Peat layer calibration (2005); (b) Till layer calibration (2005); (c) Peat layer validation (2006); (d) Till layer validation (2006).....	53
Figure 2-6 Simulated and observed moisture in the Old Aspen watershed; (a) A-Horizon calibration (2000); (b) B-Horizon calibration (2000); (c) A-Horizon validation (1999); (d) B-Horizon validation (1999).	54
Figure 2-7 Simulated and observed actual cumulative evapotranspiration for; (a) SWSS; (b) SBH; (c) OA sites, respectively.	55
Figure 2-8 Simulated and Observed daily AET values for the growing season period; (a) SWSS; (b) SBH; (c) OA sites.	56
Figure 2-9 Simulated and Observed Runoff (overland flow) of the D1 cover in 2001....	58
Figure 3-1 A flow chart of the procedure of which the GSDW model follows to accommodate various hydrological processes in top layer.....	84

Figure 3-2 Frequency curve of maximum moisture deficit of soil covers a) D1 cover, b) D2 cover, and c) D3 cover.	90
Figure 3-3 Stochastic comparison between the hydrological performances of the D1, D2, D3, and Dhyp sub-watersheds.	92
Figure 3-4 Stochastic comparison between the hydrologic performances of the OA, SBH, OJP, and SWSS sites.....	95
Figure 3-5 Stochastic comparison between the hydrological performances of the SBH site using different vegetation alternatives.	97
Figure 3-6 Frequency curve of growing season evapotranspiration fluxes.	100
Figure 4-1. Annual precipitation from NARR and D3 onsite station data, 2000-2006..	126
Figure 4-2 Observed D3 cover and NARR precipitation: (a) calibration year 2003; and (b-d) validation years 2004-2006.....	129
Figure 4-3 Daily simulated soil moisture storage for the calibration period (2003) using both models along with observed soil moisture for the D3 cover: (a) peat layer and (b) till layer.....	130
Figure 4-4 Daily simulated soil moisture storage for the validation period (2004-2006) along with observed soil moisture for the D3 cover: (a) peat layer and (b) till layer.....	132
Figure 4-5 Daily simulated soil moisture storage for the calibration period (2003), for both models, along with observed soil moisture for the SWSS site: (a) till layer and (b) tailing sand layer.....	134

Figure 4-6 Daily simulated soil moisture storage for the validation period (2005-2006) along with observed soil moisture for the SWSS site: (a) till layer and (b) tailing sand layer.	136
Figure 4-7 Simulated-NARR and observed daily ET flux values: (a) D3 cover AET flux (2004-2006); (b) SWSS watershed AET flux (2005-2006); (c) D3 cover PET (2004-2006); (d) SWSS watershed PET (2005-2006).	138
Figure 4-8 Stochastic comparison of the hydrological performance of the D3 cover based on EC and NARR datasets.	140
Figure 4-9 Stochastic comparison of the hydrological performance of the SWSS watershed based on EC and NARR datasets.	141
Figure 5-1 Probabilistic comparison of the hydrological performance of the D3 cover based on EC dataset and CGCM3 scenarios.	171
Figure 5-2 Probabilistic comparison of the hydrological performance of the SWSS watershed based on EC dataset and CGCM3 scenarios.	172
Figure 5-3 Probabilistic comparison of the hydrological performance of the OA watershed based on EC dataset and CGCM3 scenarios.	174
Figure 5-4 Frequency curve of growing season evapotranspiration fluxes for D3 cover.	176
Figure 5-5 Frequency curve of growing season evapotranspiration fluxes for SWSS site.	177
Figure 5-6 Frequency curve of growing season evapotranspiration fluxes for OA watershed.	178
Figure A.1 Location of the study sites (old jack pine, and old aspen), Saskatchewan. ..	197

Figure A.2 Photographs of double scaffold tower and hut at OA (left), and forest floor at bottom of tower at OJP site (right), during summer.	198
Figure A.3 Photographs of below (left), above (right) forest canopy conditions and a sketch showing soil layer stratification of the old aspen (top), and old jack pine (bottom) sites (Modified from Balland et al., 2006).	198
Figure A.4 Location of the reconstructed study areas (SWSS and South Hills).	205
Figure A.5 SWSS cross section comprise of 45 cm of till (dark) over 100 cm tailing sand (<i>After Izadifar, 2006</i>).	206
Figure A.6 Oil sands mining operation at Mildred Lake Area, Fort McMurray, Alberta (<i>After Izadifar, 2010</i>).	213
Figure A.7 SWSS site Eddy Covariance (EC) Tower in 2007.	213
Figure A.8 Sample of the existing vegetation at SWSS site (Summer 2009).....	214
Figure A.9 Sample of the existing vegetation at SBH site (summer 2009).....	214
Figure A.10 Sample of the existing vegetation at D3 cover (summer 2009).	215

List of Abbreviations

AT	Air temperature
AWHC	Available water holding capacity
BD	Bulk density
DA	Decision analysis
EC	Eddy-covariance
ET	Evapotranspiration
GCM	Global circulation models
GSDW	Generic system dynamics watershed model
GT	Ground temperature
H	Sensible heat flux
HRUs	Hydrologic response units
LAI	LAI leaf area index (m^2/m^2)
LE	Latent heat flux
MARE	Mean absolute relative error
NARR	North American regional reanalysis
NR	Net radiation
OA	Old Aspen
OJP	Old Jack Pine
PM	Penman-Monteith
R	Coefficient of correlation
RH	Relative humidity
RMSE	Root-mean squared error
SBH	South Bison hill
SD	System dynamics
SRS	Sustainable reclamation strategy
SWAT	Soil and water assessment tool
SWSS	South-west sand storage
WS	Wind speed

Chapter 1 - Introduction

1.1 Background

Canada's boreal forest, representing one-quarter of the world's remaining intact forest, is a complex ecosystem comprised of a unique mosaic of forest and wetlands that is home to a wide variety of wildlife. The boreal forest is also considered the largest terrestrial carbon reservoir in the world, storing approximately 22% of the total carbon in the planet's land surfaces (IPCC, 2000). Oil sands mining in northern Alberta, Canada, results in large disturbances to the boreal ecosystem as soil and overburden materials are removed and stockpiled to provide access to mined materials. The United Nations Environment Program has identified Alberta's oil sands mining initiative as one of 100 key global "hotspots" of environmental degradation (UNEP, 2006). Increased concentrations of greenhouse emissions in the atmosphere are expected to cause increases in temperature and changes in precipitation patterns (Houghton et al., 1990). The expected future climatic changes highlight the need to understand how a change in global climate could affect regional hydrological regimes.

Plans for the restoration of disturbed watersheds are mandatory to gain government consent to commence mining activity. The process of re-establishing the disturbed landscape and developing sustainable soil-vegetation-water interactions is called land reclamation (Gilley et al., 1977; Haigh, 2000; Barbour et al., 2004). Sustainable land reclamation strategies employ engineering measures to contain and control problems caused by the disruption of natural systems. Considering the current

rate of mining activities expansion, confronting the combined and cumulative impact arising from both mining activities and the projected climate change is required.

1.2 Area of interest

In sub-humid regions such as northern Alberta, where potential evapotranspiration is greater than annual precipitation, reclaimed soil covers should have the ability to minimize runoff, retain soil moisture for the growing season, and minimize deep percolation of moisture below the root zone (Swanson et al., 2003). Infiltration, soil moisture redistribution, and actual evapotranspiration (AET) are the key factors affecting hydrological processes in natural and reconstructed watersheds. Soil moisture redistribution and evapotranspiration (ET) are intricately linked; thus, understanding their interaction could lead to more accurate simulations of hydrological processes responsible for land-atmosphere interactions (Mahmood and Hubbard, 2003). Despite the importance of AET and soil moisture redistribution in defining the water balance of arid and semi-arid (or sub-humid) regions, limited literature is available, relative to the rainfall-runoff relation, on the simulation of both AET and moisture redistribution as targeted outputs of hydrological models (Elshorbagy et al., 2007).

Countless watershed models have been developed around the world for a variety of different applications; however, the main challenge remains in applying the limited and imperfect knowledge of the corresponding hydrological processes (Schaacke, 2002). The adverse impact of disturbing natural ecosystems may be intensified by the expected climate change and its projected consequences. Simulating the current hydrological

behaviour of reconstructed watersheds (variety of possible soil cover designs) as accurately as possible is important; however, the ultimate objective is to determine the expected future hydrological performance. To understand reconstructed systems efficiently and foresee their future performance, a framework is needed to link reconstructed watersheds to analogous mature natural systems and to recognize the influence of the projected future climatic scenarios on the hydrological behaviour of those watersheds. This is identified as the area of interest of this study.

1.3 Problem recognition

The emergence of the system dynamics (SD) approach has provided a better understanding of the multifarious relationships that exist among different elements within a system. SD has increasingly been adopted to help avoid judgment biases by identifying system boundaries and proper representation of physical processes (Constanza and Ruth, 1998). Recognizing that hydrological modeling can play a central role in evaluating the performance of reconstructed watersheds, Elshorbagy et al. (2005; 2007) used SD to develop a site-specific system dynamics watershed (SDW) model. Modeling studies of the hydrological performance of reconstructed watersheds in northern Alberta using the SDW model have shed some light on the issue (e.g., Bachu and Elshorbagy, 2009; Elshorbagy and Barbour, 2007; Julta, 2006), but a knowledge gap remains.

Elshorbagy and Barbour (2007) used the calibrated site-specific SDW model, along with the available historical meteorological records, to estimate the maximum soil moisture deficit during the growing season. Frequency curves of the maximum annual

moisture deficit were used to assess the probability that a soil cover (reconstructed watershed) can provide the desired threshold of moisture demand. This probabilistic approach has the potential to enable a better understanding of the response of reconstructed systems via multiple simulations of “what-if” scenarios using different soil/vegetation alternatives. It also allows for the creation of a risk-based representation of the available water holding capacity (AWHC) concept. Furthermore, a similar analysis is quite useful in the design and formation of newly reconstructed watersheds.

Most reconstructed watersheds are extensively monitored and the data collected used to build a knowledge base for future reclaimed sites; however, monitoring programs will not be continued indefinitely. Rick (1995) suggested a five year monitoring period for reconstructed watersheds with two additional years of passive management. Accordingly, availability of data is a major challenge that constrains a model’s selection, predictive ability, and accuracy. Despite the existence of long-term surface records of temperature and precipitation, the number of observations is limited and the measurements are often site-specific. Thus, simulating various hydrological processes requires a reliable and continuous source of input data in addition to *in situ* meteorological stations, especially in remote regions.

The existing site-specific SDW model must be modified to be more generic and applicable to a wider variety of reconstructed and natural watersheds in the sub-humid region of interest. The modifications should include portions missing in the existing SDW model, such as canopy interception, number of simulated soil layers, soil

stratification, and topographic inclination of the site. Furthermore, assessing the long-term performance and sustainability of the reconstructed watersheds using various sources of data, as well as under historical and projected future conditions, are important for designing sustainable reclamation strategies.

1.4 Research Objectives

To improve the credibility of hydrological process simulations (e.g., soil moisture and evapotranspiration flux) and to assess the hydrological performance of the reconstructed watersheds compared to natural watersheds, the objectives of this research are:

1. To build on the existing site-specific system dynamics watershed (SDW) model and develop a generic system dynamics watershed (GSDW) model, then subsequently adapt the GSDW model to simulate various natural forested and reconstructed watersheds;
2. To compare the long-term hydrological performance of reconstructed and natural watersheds with respect to soil moisture deficit and evapotranspiration using a probabilistic framework. Based on this comparison, knowledge can be transferred to assess the sustainability of the restored forests on newly reclaimed sites;
3. To introduce an approach that allows for testing and optimizing the design of reconstructed soil cover alternatives based on the knowledge gained from modeling the existing reconstructed sites;

4. To test the utility of the developed GSDW model and the probabilistic assessment framework using the coarse North American Regional Reanalysis (NARR) temperature and precipitation data for hydrological modeling and assessment; and
5. To implement the same probabilistic approach used in Objectives 2, 3, and 4 with statistically downscaled data from the Canadian Global Climate Model (CGCM3) under selected emission scenarios to estimate future changes in soil moisture regime and actual evapotranspiration flux.

1.5 Scope of the research program

Most reconstructed watersheds are extensively monitored and the data collected are used to build a knowledge base to help understand the predominant hydrological processes. The present work is part of a large research program that aims to develop this knowledge base, and thereby develop a sustainable reclamation strategy (SRS) that can be implemented in future reclaimed sites. The sizeable amount of collected data, although useful and desirable, can lead to paralysis of analysis in the absence of a precise framework.

The overall framework of this research program is founded on the ongoing monitoring program (Figure 1-1), a concise description of which is given here. The knowledge gained from the inductive and deductive modeling approaches of the ongoing reconstructed systems, supplemented by knowledge gained from mature natural systems, can be encapsulated together to formulate a comprehensive system understanding, a decision analysis (DA) framework, and uncertainty analyses. System understanding may

lead to re-directing the monitoring program and refining our simulation/prediction models, which in turn can be used to modify existing regulations toward developing a sustainable reclamation strategy.

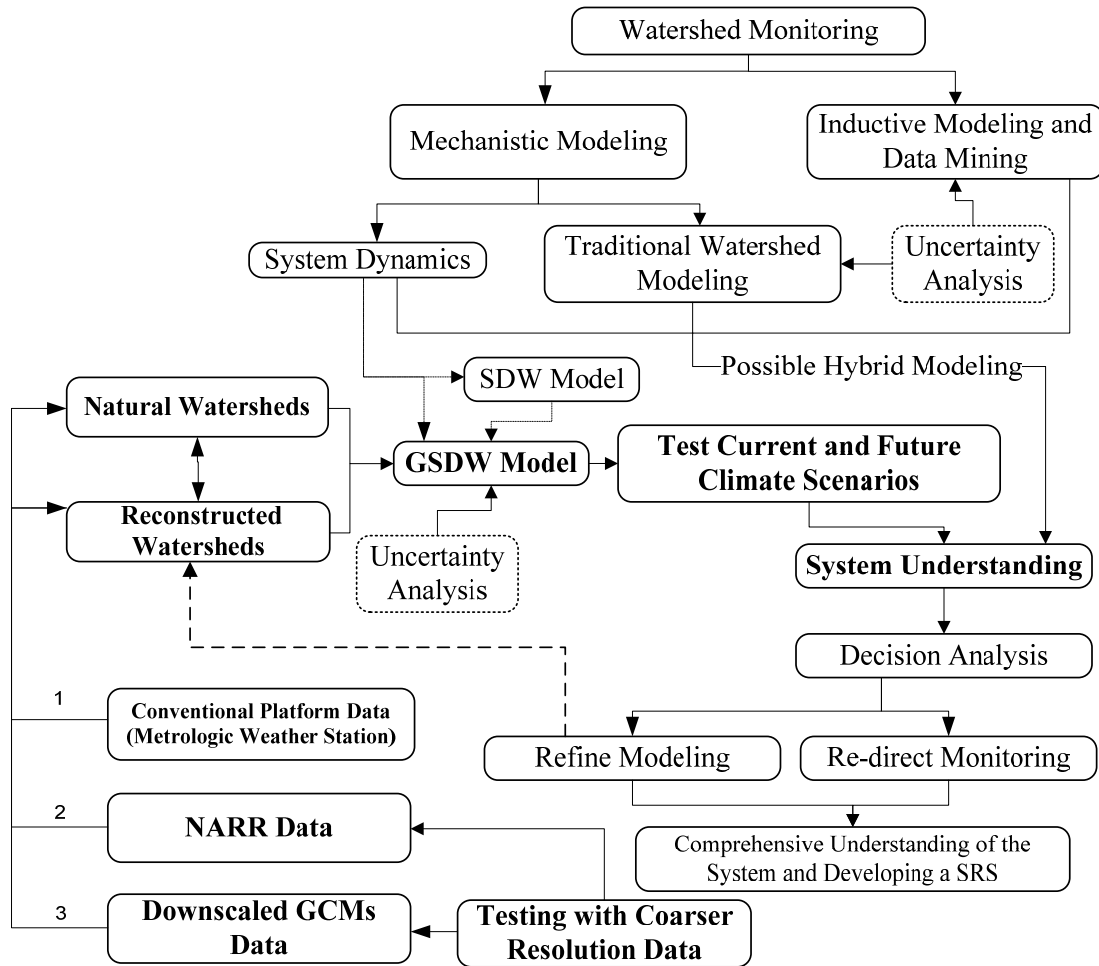


Figure 1-1 Framework of the research program for developing a sustainable reclamation strategy (SRS) (modified after Julta, 2006; Parasuraman, 2007).

The current rate of oil sands industry expansion necessitates the use of platforms (e.g., NARR) to acquire data for hydrological modeling; this is in contrast to conventional platforms (e.g., metrological weather stations) that require continuous efforts with respect to set up and maintenance, especially in remote regions. The utility of the developed model will also be tested by using meteorological inputs downscaled from the outputs of Global Climate Models (GCMs). This is required to evaluate the future performance of different reclamation strategies over time under different climate scenarios. The following tasks pertaining to the overall framework of this large scale research program:

1. Develop an in-house watershed simulation methodology using a system dynamics modeling approach that can provide a clear picture of the dynamics of reconstructed watershed hydrology. This entails developing and evaluating the performance of in-house site-specific and generic models. A site-specific watershed (SDW) model was developed by Jutla(2006) and modified by Bachu (2008);
2. Simulate the reconstructed watersheds using some of the widely-used watershed models (e.g., SWAT, SLURP), and compare their performances with the model developed in Task 1. The purpose of such a comparison is to gauge the utility of different approaches for modeling the hydrological processes of reconstructed watersheds in sub-humid regions;

3. Evaluate the added gains, if any, of adopting an inductive (data driven) approach for modeling the different components of the hydrological cycle in reconstructed watersheds. This task was conducted by Parasuraman (2007) and Izadifar (2010);
4. Simulate mature natural watersheds for comparison to analogous reconstructed watersheds. This comparison can potentially assist in identifying and filling the knowledge gap regarding the evolution of reconstructed watersheds over time. Work on this task was started by Bachu (2008);
5. Conduct a comprehensive study to identify different sources of uncertainty and find methods and tools to effectively incorporate uncertainty analysis into the watershed model building exercise;
6. Develop a hybrid modeling approach that benefits from the knowledge gained by adopting mechanistic (e.g., system dynamics) and inductive modeling approaches. The objective of this task is to develop and propose, to both industry and science, the best possible tools for modeling reconstructed watersheds;
7. Evaluate the developed models with coarser data, with the help of available global reanalyses data (e.g., NARR, a 32 km resolution grid over North America) and with the downscaled Global Climate Models (GCMs, 400 km resolution grid), to enrich the utility of the modeling approach and, in turn, allow for its adoption in directing future reclamation strategies under changing conditions; and

8. Develop a multi-criterion decision analysis (MCDA) framework capable of evaluating different reclamation alternatives. The objective of this task is to encapsulate the knowledge gained with regard to reconstructed watersheds into a decision analysis tool, which can be adopted to redirect monitoring programs, refine modeling practices, and orient future reclamation strategies. Work on this task was started by Elshorbagy (2006).

The scope of this research is confined to completing the deductive modeling approach (Task 1) for building a generic system dynamics watershed (GSDW) model and to addressing the issue of using coarser data and climate change in hydrological modeling (Task 7). An attempt to compare the performance of the developed model with SWAT was conducted (Task 2), and analysis of the long-term hydrological performance of reconstructed and analogous mature natural watersheds was also completed (Task 4). These are identified in bold text in Figure (1-1).

This research may not address in depth all pertinent issues with regard to designated tasks. Nevertheless, this research serves as a “step forward” and will inform future studies in this direction.

1.6 Synopsis of the thesis

Chapters in this thesis are ordered in accordance with the research objectives. Chapter 2 addresses the first objective, Chapter 3 addresses the second and third

objectives, and Chapters 4 and 5 address the fourth and fifth objectives. The contents of the various chapters of this thesis are outlined more specifically below.

Chapter 2 presents the proposed GSDW model development and formulations. The ability of the proposed GSDW model to reproduce the hydrological behaviour of reconstructed and natural watersheds is elucidated through modeling soil moisture content and actual evapotranspiration. Chapter 3 highlights the methodology of long-term simulations and the probabilistic assessment of reconstructed and natural watersheds based on the soil moisture deficit and the actual evapotranspiration flux. This chapter demonstrates the usefulness of adopting this approach for better understanding of the response of reconstructed systems via multiple simulations of “what-if” scenarios using different soil/vegetation alternatives. Chapter 4 underscores the utility of adopting the NARR data against conventional platforms (meteorological stations) in hydrological modeling. The NARR long-term dataset (1979-2006) is also used to assess the long-term hydrological performance of reconstructed watersheds. Chapter 5 presents the development of a generalized understanding of the sensitivity of soil moisture patterns to changes due to the projected variation in precipitation and temperature patterns in the 21st century. Downscaled daily precipitation and air temperature outputs from global climate models (CGCM3), under A2 and B1 emission scenarios, are used to evaluate the future hydrological performance of the designated watersheds with respect to soil moisture deficit and evapotranspiration. Finally, in Chapter 6, a brief summary of the thesis and its contribution to the existing body of knowledge are highlighted. Some implied limitations of this research and the scope for further studies are also discussed.

1.7 References

- Bachu, L. and A. Elshorbagy, 2009. Hydrology of Reconstructed and Natural Watersheds. Modeling Based Comparative Analysis of Hydrological Performance. *VDM Verlag Dr. Muller, Saarbrücken, Germany*, pp. 118
- Bachu, L., 2008. A comparative analysis of the hydrological performance of reconstructed and natural watersheds. MSc thesis, Dept. of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, SK, Canada.
- Barbour, S.L., D. Chapman, C. Qualizza, S. Kessler, C. Boese, R. Shurniak, G. Meiers, M. O’Kane, J. Hendry and S. Wall, 2004. Tracking the evolution of reclaimed landscapes through the use of instrumented watersheds – a brief history of the Syncrude Southwest 30 Overburden Reclamation Research Program. *Proceedings of the International Instrumented Watershed Symposium*, Edmonton, Canada, www.rr.ualberta.ca/oilsands/IIWS.htm.
- Costanza, R. and M. Ruth, 1998. Using dynamic modeling to scope environmental problems and build consensus. *Environmental Management*, 22(2):183–195.
- Elshorbagy A., A. Jutla, and J. Kells, 2007. Simulation of the hydrological processes on reconstructed watersheds using system dynamics. *Hydrological Science Journal*, 52(3):538–561.
- Elshorbagy, A. and S.L. Barbour, 2007. A probabilistic approach for design and hydrologic performance assessment of reconstructed watersheds. *Journal of Geotechnical & Geoenvironmental Engineering ASCE*. 133(9):1110–1118.

- Elshorbagy, A. 2006. Multi-criterion Decision Analysis Approach to Assess the Utility of Watershed Modeling for Management Decisions. *Water Resources Research*, 42, W09407, doi:10.1029/2005WR004264.
- Elshorbagy, A., A. Jutla, L. Barbour and J. Kells, 2005. System dynamics approach to assess the sustainability of reclamation of distributed watersheds. *Canadian Journal of Civil Engineering*, 32:144–158.
- Gilley, J.E., G.W. Gee, A. Bauer, W.O. Willis and R.A. Young, 1977. Runoff and erosion characteristics of surface mined sites in western North Dakota. *Transactions of American Society of Agricultural Engineers*, 20(4):697–704.
- Haigh, M.J., 2000. The aims of land reclamation, Land reconstruction and management. A. A. Balkema Publishers, Rotterdam, The Netherlands, 1:1–20.
- Houghton, J.T., G.J. Jenkins and J.J. Ephraums, 1990. Climate Change. The IPCC Assessment, Cambridge University Press.
- Izadifar, Z., 2010. Modeling and analysis of actual evapotranspiration using data driven and wavelet techniques. MSc thesis, Dept. of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, SK, Canada.
- IPCC (Intergovernmental Panel on Climate Change), 2000. Land Use, Land-use change and forestry. R.T. Watson, I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo, and D.J. Dokken (eds.). Cambridge University Press, Cambridge, U.K.
- Jutla, A., 2006. Hydrologic modeling of reconstructed watersheds using a system dynamics approach. MSc thesis, Dept. of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, SK, Canada.

- Mahmood, R., and K.G. Hubbard, 2003. Simulating sensitivity of soil moisture and evapotranspiration under heterogeneous soils and land uses. *Journal of Hydrology*, (280):72-90.
- Parasuraman, K. (2007). Hydrological Prediction using pattern recognition and soft-computing techniques. Ph.D Thesis, University of Saskatchewan, Saskatoon, SK, Canada.
- Rick, G., 1995. Closure considerations in environmental impact statements. *Mineral Industry International*, (1022):5-10.
- Schaake, J.C., 2002. Calibration of watershed models-Introduction. Duan et. al. (ed.), *Water Science and Application 6, AGU*, Washington, DC., 1-7.
- Swanson, D.A., S.L. Barbour, G.W. Wilson, and M. O'kane, 2003. Soil-atmosphere modelling of an engineered soil cover for acid generating mine waste in a humid, alpine climate. *Canadian Geotechnical Journal*, 40(2):276-292.
- United Nations Environment Programme (UNEP), 2006. Flying around the globe on a time machine.
<http://www.unep.org/Documents.Multilingual/Default.asp?DocumentID=487&ArticleID=5350&l=en>).

Chapter 2 - A Generic System Dynamics Model for Simulating and Evaluating the Hydrological Performance of Reconstructed Watersheds

This chapter has been as a research paper in the *Hydrology and Earth System Sciences (HESS) Journal*.

Citation: Keshta, N., Elshorbagy, A. and Carey, S. (2009). A generic system dynamics model for simulating and evaluating the hydrological performance of reconstructed watersheds. *Hydrology and Earth System Sciences* 13(6):865–881.

Contribution of the PhD candidate

Conceptualizing and development of the generic system dynamics watershed (GSDW) model were carried out by the candidate, with the second author (the Ph.D. supervisor) providing advice on various aspects of the work. The text of the published manuscript was drafted by the candidate with the second author offering critical review and editorial guidance. The third author carried out the preliminary evapotranspiration raw data quality checks, provided the site description details, and also offered editorial review of the manuscript.

Contribution of this chapter to the overall study

This work was intended to develop a lumped GSDW model. The resulting developed model is an upgrade of the site-specific system dynamics watershed (SDW) model, initially developed by Elshorbagy et al. (2005), to accommodate canopy interception, varying number of soil layers, stratification, and topographic inclination of

the site. A provision was made in this model for interflow and runoff components to account for the effect of surface slope, and the van Genuchten (1980) equation was implemented in the model structure to describe the soil water characteristic curves (SWCC). In this chapter, the improvement in the reliability of simulating the hydrological processes achieved by adopting the GSDW model was tested against a widely used hydrological model entitled Soil and Water Assessment Tool (SWAT). The GSDW model was shown to be an effective tool for simulating soil moisture patterns and evapotranspiration flux in a wide spectrum of natural and reconstructed watersheds.

2.1 Abstract

A generic system dynamics watershed (GSDW) model is developed and applied to five reconstructed watersheds located in the Athabasca mining basin, Alberta, Canada, and one natural watershed (boreal forest) located in Saskatchewan, Canada, to simulate various hydrological processes in reconstructed and natural watersheds. This paper uses the root mean square error (RMSE), the mean absolute relative error (MARE), and the correlation coefficient (R) as the main performance indicators, in addition to the visual comparison. For the South Bison Hills (SBH), South West Sand Storage (SWSS) and Old Aspen (OA) simulated soil moisture, the RMSE values ranges between 2.5-4.8 mm, and the MARE ranges from 7% to 18%, except for the D2-cover where it was 26% for the validation year. The R statistics ranges from 0.3 to 0.77 during the validation period. The error between the measured and simulated cumulative actual evapotranspiration (AET) flux for the SWSS, SBH, and the OA sites were 2%, 5%, and 8%, respectively. The developed GSDW model enables the investigation of the utility of different soil cover designs and evaluation of their performance. The model is capable of capturing the dynamics of water balance components, and may used to conduct short- and long- term predictions under different climate scenarios.

2.2 Introduction

Hydrological models have been adopted, modified, and applied to solve a wide spectrum of problems. The difficulty of modeling watershed hydrology lies primarily in that the response of the watershed system is strongly controlled by its spatial and temporal heterogeneity, and this heterogeneity cannot be precisely known or described. In general, the focus of watershed modeling studies has been on rainfall-runoff relations (Beven, 2001). Over the past few decades, countless numbers of watershed models have been developed around the world for a variety of applications. However, the main challenge remains in applying limited and imperfect knowledge of hydrological processes while providing an acceptable prediction of the real world (Schaacke, 2002). Hydrological processes such as soil moisture redistribution and evapotranspiration (ET), are intricately linked; therefore, the understanding of their mutual interaction could lead to a more accurate simulation of the processes responsible for land-atmosphere interaction (Mahmood and Hubbard, 2003).

As natural ecosystems are complex, their characteristics and dynamic properties depend on many interrelated links between climate, soil and vegetation (Rodriguez-Iturbe et al., 2001). Soil and climate control vegetation dynamics, while in turn vegetation modulates the water balance (Porporato and Rodriguez-Iturbe, 2002; Arora, 2002). Vegetation acts as the intermediate link between soil and the atmosphere via evapotranspiration, as well as affecting soil hydraulic and mechanical properties. Moreover, it affects both the surface energy budget and soil storage in the root zone (Falkenmark, 1997). Several models have been used to simulate soil-atmospheric-

vegetation interaction, e.g. Soil-Vegetation-Atmosphere Transfer schemes (SVAT). SVAT model is used to simulate, energy, carbon, and water fluxes, typically assuming static vegetation (Arora, 2002). Other models used to simulate agriculture management scenarios (e.g. SWAT) are devoted to reproducing crop growth, nutrient and pesticide practice, yet are data intensive to implement (Neitsch et al., 2002). Recently, Quevedo and Francés (2008) used a conceptual dynamic vegetation-soil model (called HORAS) for arid and semi-arid zones. The HORAS model consists of two reservoirs; the first for the interception process and the second for near-surface soil moisture. The HORAS model excelled in demonstrating the adaptation of vegetation to various climatic and soil conditions. However, it simulates only the upper capillary water-soil content where vegetation occurs unless it is coupled with a more comprehensive hydrological model (Quevedo and Francés, 2008).

Infiltration, soil moisture redistribution, and ET are the main hydrological processes affecting the behavior of natural and restored (reconstructed) watersheds in arid and semi- arid regions. Hence, the proper simulation of these processes is vital to the accurate representation of the hydrology of both watersheds (Elshorbagy et al, 2007; Quevedo and Francés, 2008). Despite the importance of ET and soil moisture redistribution in defining the water balance of the arid and semi-arid regions relative to the rainfall-runoff relation, there is limited literature available on the simulation of these processes. In addition, both ET and soil moisture dynamics have an important role in the ecological behavior of reconstructed watersheds following mining.

The rapid growth of the oil sands industry results in large disturbances to the natural ecosystem as soil and overburden materials are removed to provide access to mining materials. The mining process is followed by a remediation process, through which the disturbed landscape is recovered with the intent to replicate the performance of natural watersheds functions such as *habitat function* (hosting aquatic ecosystems), *production function* (e.g., biomass), and *carrier function* (for dissolved and suspended material), this process is also known as land reclamation (Haigh, 2000; Barbour et al., 2004). The adverse impact of disturbing the natural ecosystem can be intensified by climate change and its projected consequences. Consequently, it is crucial to simulate and predict, as accurately as possible, the hydrological behaviour of the reconstructed watersheds. Watershed models provide a vital tool that can assist in achieving this goal by simulating the hydrological behaviour of a variety of possible soil cover designs. The aim of this paper is to develop a generic system dynamics watershed model (GSDW), which provides a reliable, simple, and comprehensive tool that facilitates the assessment of the sustainability of various reconstructed/natural watersheds. The validity of the proposed model is assessed thorough its capability in reproducing the hydrological behaviour of the reconstructed and natural watersheds. The proposed model can be used to aid in decision making and contribute to the understanding of the complex hydrological processes of the reconstructed systems, especially in arid and semi-arid regions. In those regions, land reclamation is affected by the local climates where potential evapotranspiration is greater than the annual precipitation. Subsequently, the designed soil covers should have the ability of minimizing runoff, and retaining soil moisture for the growing season.

2.3 Modeling of Reconstructed Watersheds

In general, the literature on reconstructed watersheds emphasizes geotechnical perspectives, and Julta (2006) noted that most publications targeted modeling an individual component of the hydrological cycle. For example, HELP (Hydrological Evaluation of Landfill Performance) is a widely applied landfill water budget model (Yalcin and Demirer, 2002). Berger et al. (1996) used HELP to simulate the water balance of a landfill cover system, where they achieved good simulation of lateral drainage, yet failed to model the liner leakage of comprehensive soil liners. The model only applies to simple covers, considers only grass as the vegetation type, and has a poor performance in estimating the long-term hydrologic processes (Berger, 2000).

The root zone water quality model (RZWQM) was used to simulate the volumetric soil water content of the reconstructed slopes of the South West Sand Storage (SWSS) in northern Alberta (Mapfumo et al., 2006). This model is used extensively in many agricultural studies; however, it tends to overestimate the saturated hydraulic conductivity and accordingly underestimates the surface soil moisture contents, especially in wet conditions. Furthermore, the soil-atmosphere model (SoilCover) (Geoanalysis 2000 Ltd., 2000) was used, by Shurniak (2003), to predict moisture movement in a variety of reconstructed soil cover systems. Shurniak (2003) recommended that the overall cover thickness to be more than 0.6 m to improve plant survival.

Finally, Elshorbagy et al. (2005) developed a site-specific system dynamics watershed (SDW) model to simulate hydrological processes using a daily time-step in reconstructed watershed in northern Alberta, Canada. This model was extended by Elshorbagy et al. (2007) to simulate three prototype watersheds, however, the model remained site-specific. Elshorbagy and Barbour (2007) presented a probabilistic approach, using the SDW model, to assess the long-term hydrologic performance of three inclined reconstructed watersheds. The validated SDW model was used along with the available meteorological historical data to generate continuous simulated records of the daily depth-averaged soil moisture content. These records were used to estimate the maximum annual moisture deficits as indicators of the hydrologic performance of the considered watershed. The probabilistic approach was not used to quantify the predictive uncertainty of the SDW model. However, the efficiency of this approach depends on the reduction of the predictive uncertainty of the model, which can be mitigated through a generic model that can simulate various reconstructed and natural watersheds under potential and uncertain changes of the prevailing climatic conditions.

2.4 GSDW Model Development and Formulation

The proposed GSDW model is a lumped conceptual model capable of simulating various components of watershed hydrology. This model is an upgrade/generalization of the existing site-specific SDW model, which was developed by Elshorbagy et al. (2005; 2007). The main drawback of the previous SDW model was that it did not account for a canopy interception. Moreover, the SDW model has no flexibility in choosing the number of soil layers (three layers only), layer thickness, and topographic

inclination. The GSDW model uses sets of meteorological, vegetation, and hydrological data to evaluate different hydrological processes on a daily basis. The model is entitled “generic” in the sense that it can be implemented on a wide spectrum of watersheds, soil cover alternatives, and topographic conditions in semi-arid regions for the purpose of assessing the performance of reconstructed watersheds. The system dynamics simulation environment (STELLA), (HPS, 2001), was used for modeling the watershed as a dynamic system in a user-friendly environment.

The system dynamics (SD) approach is based on the understanding of the complex relationships existing among the different elements within the considered system. In general, the SD approach can be defined as: “a theory of system structure and a set of tools for representing complex systems and analyzing their dynamic behavior” (Forrester, 1980a and 1980b). Ford (1999) defined the SD approach as a method of analyzing problems in which time is an important factor. The main issue in using SD is to understand the system and its boundaries by identify its key building blocks, and the proper representation of the physical processes through relatively accurate mathematical relationships. SD models have the potential of implementing a combination of empirical formulations and physically based concepts and also allows for building on a tentative knowledge of the relation between two parameters by incorporating a qualitative relationship between those parameters (Elshorbagy et al., 2007). The proposed GSDW model will have the ability to simulate relevant hydrological processes, e.g., canopy interception, evapotranspiration, surface runoff, lateral interflow, infiltration, and soil moisture redistribution in unsaturated/saturated layers, based on the surface energy and

water balances. Particular attention is given to the parameterization, which is kept as simple as possible and reliant on widely available data. A schematic diagram of the major processes modelled by the proposed GSDW model is shown in Figure 2-1.

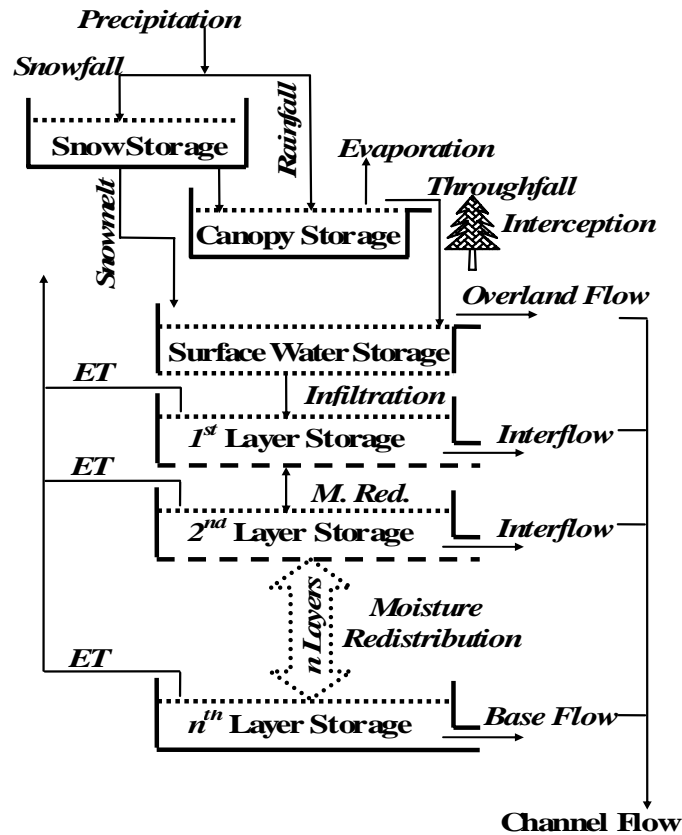


Figure 2-1 A schematic diagram of the GSDW model structure.

Figure 2-1 shows the simple daily water balance of the GSDW model, which consists of three storage components: (1) canopy storage, (2) surface storage, and (3) soil storage. The system dynamics hypothesis of the developed GSDW model is represented in a causal-loop diagram (Figure 2-2). The feedback loops illustrate the mutual

interaction among the different factors affecting watershed hydrological processes. Negative and positive signs denote the type of relationship between corresponding variables.

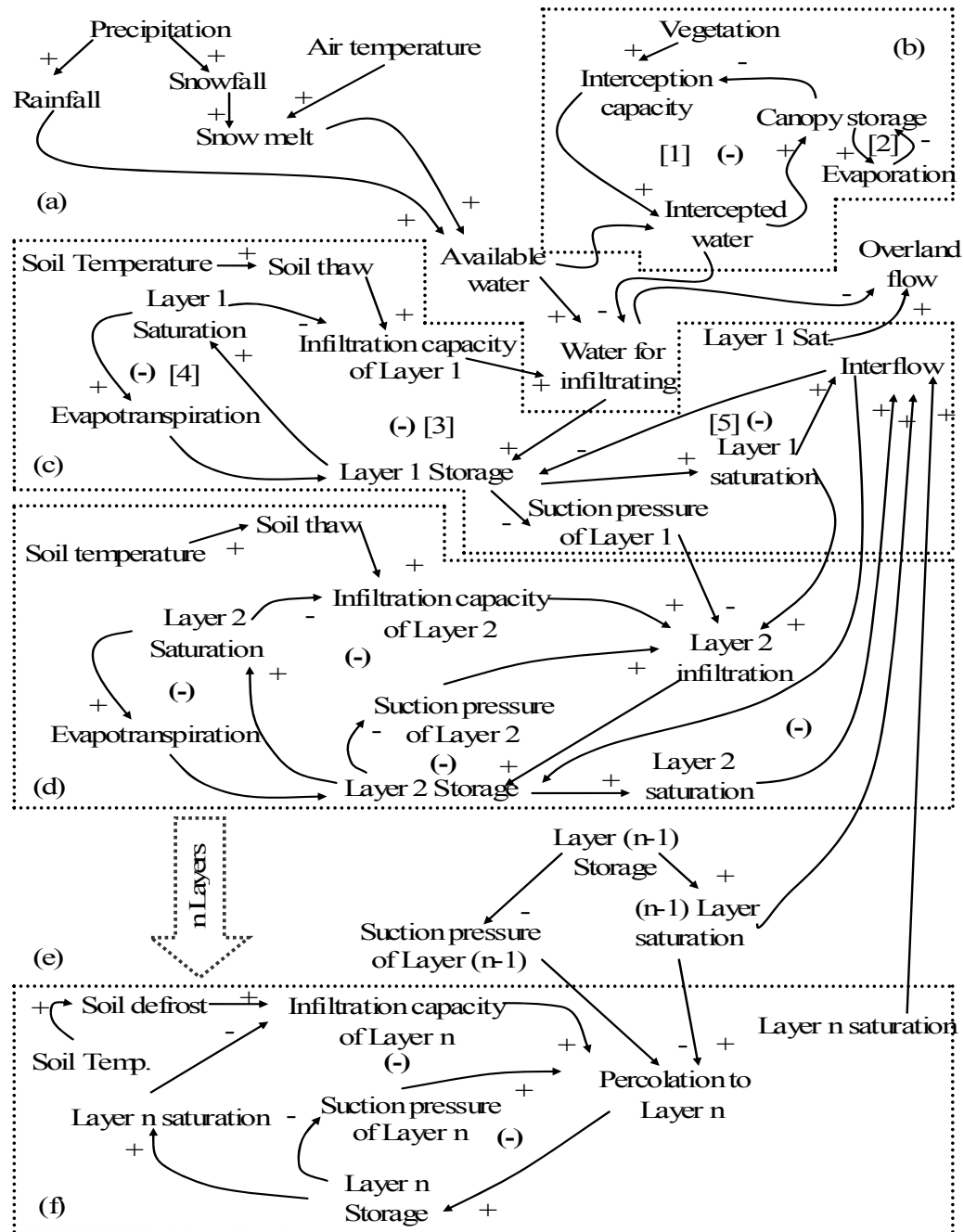


Figure 2-2 Causal-loop diagram of the developed GSDW model.

Figure 2-2 is partitioned into several parts; (a) available water (snowfall and rainfall), (b) canopy interception, and (c-f) soil layers and the surface and subsurface (vertical/horizontal) water movement. The following outlines modifications and improvements suggested to the SDW model, whose details can be found in Elshorbagy et al. (2005; 2007).

2.4.1 Canopy storage

Interception losses range from 10-40% of gross precipitation for different vegetation types (Dingman, 2002). Therefore, consideration of interception losses will improve AET predictability of the developed model. One challenge posed by the incorporation of vegetation processes in hydrological models is the incorporation of new parameterizations. The explicit representation of vegetation dynamics in hydrological models implies the specification of a large number of parameters. Two different approaches are used to incorporate the canopy interception component, based upon the data availability; (i) a simplified version of Valente et al. (1997) conceptual model, and (ii) the van Dijk and Bruijnzeel (2001) analytical model. Valente et al. (1997) developed a conceptual model, where the canopy interception component divides the gross rainfall into three downward water fluxes: (1) free throughfall, (2) canopy drip, and (3) stem-flow. This is in addition to a vertical direct evaporation component. The canopy structure is characterised by four parameters, namely: (i) canopy storage capacity, (ii) trunk storage capacity, (iii) canopy cover fraction, and (iv) trunk diversion coefficient.

The GSDW model includes the corresponding parameters representing the aforementioned physical characteristics, such as the canopy storage capacity (S_c), trunk storage capacity (S_t), trunk evaporation as a fraction of the total evaporation (ε). These parameters are based on detailed information of the vegetation structure. The leaf area index (LAI) is used as an indicator of the canopy interception, which can be deduced based on the ratio of the canopy shaded areas to the bare areas. The evaporation rate from the canopy (E_c) is computed as the sum of both the trunk and the canopy evaporation. The Penman equation is used to compute the rate of evaporation (E_p) of the intercepted water. Equations 2.1, 2.2, and 2.3 are the mathematical representation of the evaporation rates from different canopy components:

$$E_{cc} = \begin{cases} (1 - \varepsilon) \cdot E_p \cdot [C_c(t)/S_c] & \text{for } C_c(t) < S_c \\ (1 - \varepsilon) \cdot E_p & \text{for } C_c(t) \geq S_c \end{cases} \quad (2.1)$$

$$E_{ct} = \begin{cases} \varepsilon \cdot E_p \cdot [C_t(t)/S_t] & \text{for } C_t(t) < S_t \\ \varepsilon \cdot E_p & \text{for } C_t(t) \geq S_t \end{cases} \quad (2.2)$$

$$E_c = (E_{cc} + E_{ct})F \quad (2.3)$$

where E_{cc} is evaporation from leaves (mm), $C_c(t)$ is the actual amount of water stored on the canopy leaves in mm, E_{ct} is the trunk evaporation (mm), $C_t(t)$ is the actual amount of water stored on the trunk in mm, and F is the fraction of area covered by the forest canopy. The main practical drawback of the Valente et al. (1997) model lies in its extensive data requirements.

The van Dijk and Bruijnzeel (2001) model; based on a modification of Gash et al. (1995) interception model, retains some of the simplicity of the empirical approaches. It is based mainly upon the LAI, and the canopy storage (S_c). The model assumptions are: (i) the ratio of the average evaporation rate over average rainfall intensity (relative evaporation rate), \bar{E}/\bar{R} can be expressed as a function of LAI, (ii) the canopy storage capacity (S_c) is linearly related to LAI, and (iii) the LAI was treated as static value during the growing season for each case study. This approach is represented in the GSDW model by the following:

$$S_c = S_L LAI \quad (2.4)$$

$$c = 1 - e^{-k \cdot LAI} \quad (2.5)$$

$$E_c = c \cdot E_p \quad (2.6)$$

where S_L denotes the specific leaf storage (the depth of water retained by the leaf per unit LAI). The S_L -values, as suggested by Pitman (1989), range between (0.4-5.88), c is the canopy cover fraction, k is the extinction coefficient and it depends on the leaf inclination angle and distribution, the k -values ranges between 0.2 and 0.8, and E_p is the Penman potential evapotranspiration. The GSDW model provides the user with the flexibility to use either one of the previous two approaches based on available data, in addition to a third selection, where the canopy interception is not incorporated due to the lack of information regarding the canopy coverage, or the absence of canopy in the case of newly reconstructed watersheds.

2.4.2 Surface water storage

The change in the surface water storage (SW) can be expressed by:

$$\frac{d(SW)}{dt} = P - f_{L1} - O_F \quad (2.7)$$

where P (mm/day) represents precipitation, in either the form of snow or rainfall, f_{L1} is the infiltration rate to the top soil layer (mm/day), and O_F represents overland flow in mm/day.

2.4.3 Soil water storage

The developed GSDW model is designed to facilitate the consideration of multiple layers of soil cover, as opposed to pre-set number of covers in the SDW model. This expands the applicability of the model to simulate a wide variety of alternatives, in addition to, enhancing soil moisture predictability. Therefore, the vertical movement of the soil moisture between any two subsequent layers is described by considering layer (i) as a control volume in the water balance. For example, the change of the moisture storage in the i^{th} layer depends on downward movement of water from the upper $i-1^{\text{th}}$ layer, evapotranspiration, interflow from the i^{th} layer, and the downward water movement to the underlying $i+1^{\text{th}}$ layer. Therefore, the change of moisture storage in the i^{th} layer can be expressed as follows:

$$\frac{dS_i}{dt} = f_i - f_{i+1} - ET_i - I_i \quad (2.8)$$

where S_i is i^{th} layer storage in mm, f_i is the downward water movement rate of the i^{th} layer, f_{i+1} is the downward water movement rate to the underlying layer in mm/day, I_i is the interflow rate for of the i^{th} layer in mm/day, and ET_i is the evapotranspiration rate from i^{th} layer in mm/day.

Voinov et al. (2004) suggested that infiltration rate of the top soil layer is equal to rainfall intensity before soil saturation is reached. In fact, some studies suggested that the rate of infiltrated water from a typical cover system is correlated to the degree of saturation of the soil, soil moisture retention characteristic, and climatic factors (e.g. rainfall) (Milczarek et al., 2000; Milczarek et al., 2003). On the other hand, the Green–Ampt equation governs the vertical movement of water during the saturation stage under the condition of soil temperature being greater than zero (unfrozen soil). The infiltration capacity (rate) based on total infiltration volume is expressed by the Green–Ampt equation in the case of a thawed saturated soil (Dingman, 2002):

$$f_i = K_{si} \left(1 + \frac{(\theta_{si} - \theta_{ii})\psi_i}{F_i} \right) \quad (2.9)$$

where K_{si} is the saturated hydraulic conductivity of the i^{th} layer in mm/day, θ_{si} is the saturated moisture content of the i^{th} layer (%), θ_{ii} is the initial moisture content of

the i^{th} layer (%), ψ_i is the suction pressure head at the wetting front in the i^{th} layer in mm, and F_i is the cumulative volume of infiltration in the i^{th} layer in mm.

There are methods for quantifying infiltration into frozen soils; however such methods are highly data-intensive (Elshorbagy et al., 2007). Other studies suggest that the frozen soil layer does not impede infiltration (Iwata et al., 2008). An empirical approach for snowmelt infiltration was suggested by Li and Simonovic (2002) and has been validated by Julta (2006). This approach is based mainly upon the idea that infiltration rates in frozen soils are influenced by temperature and temperature accumulation. The infiltrated water will gain its dynamics based upon the temperature index, where soil will refreeze if the temperature drops below zero for a certain number of days. The active temperature accumulation will be lost and will start again from zero (Li and Simonovic, 2002). Consequently, infiltration into frozen soil is computed by multiplying infiltration rate of the i^{th} layer, f_i , by an empirical coefficient, C_{fi} . Reference is made to Elshorbagy et al. (2007) for further details.

The movement of water between any two layers is limited if the layer moisture content is less than the residual moisture content. Moisture movement will start when the upper layer moisture is greater than the residual moisture content, and it starts contributing to the lower layer moisture until it reaches saturation. Once the lower layer reaches saturation, the maximum rate at which water can be absorbed by the lower layer will correspond to the minimum value of the saturated hydraulic conductivity of this layer and the subsequent layer. Otherwise, the following logic will apply:

if (soil temperature of (i) greater than 0 °C)

then (if ($\Psi_{i-1} > \Psi_n$))

then (no movement of water)

else (if ($\theta_{i-1} > \text{residual soil moisture of (i-1) layer}$))

then (if ((i-1) layer is saturated)

then (Min (drainable water from layer (i-1), f_i Equation (2.9)))

else (follow Equation (2.10)))

else (no movement of water))

else (infiltration in frozen soil)

where, Equation 2.10 is an empirical equation, which can be written as follows (Elshorbagy et al., 2007):

$$f_i = \frac{\theta_{i-1}}{\theta_i} \frac{S_{i-1}}{\Delta t} I_{ci} \quad (2.10)$$

where I_{ci} is the coefficient of the i^{th} layer infiltration, which is determined during calibration of the model, and Δt is the solution time interval. Equation 2.10 suggests that the moisture redistribution between any subsequent layers is strongly dependent on the moisture contents of both layers. In addition, no downward moisture movement is allowed if the suction of the upper layer is greater than that of the lower layer.

2.4.4 Evapotranspiration module

In the model, the potential evapotranspiration is computed using the Penman equation derived in Mays (2005), while an empirical formula is used for the actual evapotranspiration calculation, based on the simulated soil moisture index, and the air temperature. To calculate the actual evapotranspiration from any soil layer; an empirical formulation used by (Julta, 2006; and Elshorbagy et al., 2007) takes into consideration the available moisture, air and soil temperatures.

$$ET_i = c_p \cdot S_{ms(i)}^{\lambda(i)} \cdot T \cdot C_{t(i)}$$

$$S_{ms(i)} = \frac{S_{(i)} / S_{N(i)} - S_{(i)rs}}{1 - S_{(i)rs}} \quad (2.11)$$

where c_p is the evapotranspiration coefficient (mm/°C/day), $S_{ms(i)}$ is the effective moisture saturation in layer (i) (dimensionless), λ is the exponential coefficient that expresses the impact of water saturation on evapotranspiration, $S_{(i)}$, $S_{N(i)}$, and $S_{(i)rs}$ are the water storage, the nominal water storage (mm), and minimum storage that can be attained (residual moisture) in layer (i), respectively.

Sankarasubramanian (2002) noted that the classical actual evapotranspiration relationships perform poorly for basins with low soil moisture storage capacity. However, the previous empirical formulas provided a better simulation than the conventional Penman equation (Elshorbagy et al., 2007). These parametric empirical equations provide better estimates of the actual evapotranspiration due to their dependence on the soil

moisture content of the considered layer. The GSDW model adjoins both the estimated E_c from the canopy storage and from different soil layers (net AET) to model the total actual evapotranspiration (AET).

2.4.5 Interflow component

The interflow component is restricted to the incidence of sloping layers. The model formulations account for the angle of inclination, which affects the interflow rate. Interflow (I_i , mm/day) from the i^{th} layer is estimated using the following modified empirical formula, used by Elshorbagy et al. (2007) as follows:

$$I_i = \left(\frac{S_i}{\Delta t} - \frac{\theta_{si} D_i}{\Delta t} \right) \cdot C_i \cdot C_{Slope} \quad (2.12)$$

where C_{Slope} is the slope coefficient that depends on the slope value. D_i is the depth of the i^{th} layer in mm, and C_i is the interflow coefficient, which is also a calibration parameter. Interflow generation is restricted to two conditions; the temperature of both layers, (i) and ($i-1$), are above zero and the i^{th} layer is saturated. If the previous conditions are fulfilled, then interflow is computed by multiplying the interflow coefficient by the available water in the i^{th} layer above saturation level and the slope coefficient. However, if the temperature of layer ($i-1$) is below 0°C and the i^{th} layer storage is between saturation and field capacity, then interflow is computed by multiplying the interflow coefficient by the drainable water in layer (i) and the slope coefficient.

Another alternative for computing the interflow component was incorporated to the model structure based on two-dimensional kinematic storage model for subsurface flow along a steep hill slope (Sloan and Moore, 1984). This module is adopted to calculate subsurface flow in a variety of hydrological models, e.g. SWAT, based on the mass continuity equation (Neitsch et al., 2002). Sloan and Moore (1984) prescribed high hydraulic conductivities in surface layers and an impermeable or semi-permeable layer at a shallow depth. The saturated thickness (H_o) normal to the bottom of the slope is expressed as:

$$H_o = \frac{2 * \text{drainable water}}{(\phi_d * L_{Hill})} \quad (2.13)$$

where ϕ_d is the drainable porosity of the soil layer (dimensionless) and is equal to the difference between the total porosity of the soil layer (dimensionless) and the porosity when the layer is at field capacity (dimensionless), L_{Hill} is the hill slope length in mm, and drainable water from the layer is the stored water above field capacity. The drainable water from the layer is calculated using the following:

if (*layer storage* \leq *layer's field capacity water content*)

then (no movement of water)

else (*layer storage* - *layer's field capacity water content*)

The Interflow at the hill slope outlet, I_i in (mm/day) for layer i , is:

$$I_i = 48 \cdot \left(\frac{\text{drainable water}_i * v_{Lat(i)}}{\phi_{d(i)} * L_{Hill}} \right) \quad (2.14)$$

$$v_{Lat} = K_{si} * Hill\ Slope$$

where v_{Lat} is the velocity of flow at the outlet. The GSDW model allows user to select between Sloan and Moore (1984) technique and the modified Elshorbagy et al. (2007) empirical formula.

2.4.6 Overland flow component

Overland flow (OF) is estimated using a modified empirically based equation from the SDW model. Since the model structure uses reservoir-based mechanisms to simulate the different hydrological processes, water in excess of infiltration capacity (saturation condition) of the first layer is directed as overland flow in the summer, and it is computed as:

$$O_F = \left(\frac{SW}{\Delta t} - f_{L1} \right) \cdot C_{Slope} \quad (2.15)$$

where f_{L1} layer (1) infiltration rate, O_F is the overland flow in mm/day.

Overland flow generation is also dependent upon the air/soil temperature and the gradient of the soil cover.

2.5 Case Studies

2.5.1 Reconstructed watersheds

The GSDW model is used to simulate the hydrological performance of various watersheds to validate its capability in capturing the dynamics of the various water balance components in different sites. Verifying the ability of the GSDW model to simulate both reconstructed and natural watersheds confirms the utility of the proposed model to conduct short- and long-term predictions under different climatic conditions. The reconstructed watershed study areas are located in north of Fort McMurray (57°39'N and 111°13'W), northern Alberta, Canada. The oil sands industry has developed a system for stabilizing the surface of the reconstructed soil covers that enables re-vegetation. A few reconstructed watersheds formed of various soil covers (various soil types, layering, and depths) are selected for this study: the first site includes three inclined prototype soil covers (D1, D2, and D3-Covers). The three covers were constructed with a thickness of 0.5 m, 0.35 m, and 1.0 m composed of 0.2 m, 0.15 m, and 0.2 m of peat/mineral mix overlying 0.3 m, 0.2 m, and 0.8 m thickness of glacial till, respectively, overlying saline sodic shale. The purpose of these experimental covers is to evaluate the performance of different alternatives in terms of moisture holding capacity and sustaining the vegetation. The three covers have a slope of 5H:1V with an area of 1 ha each. These covers were constructed in 1999 and seeded with barley nurse crop (*Hordeum Jubatum*), and tree seedlings of white spruce (*Picea glauca*) and aspen (*Populus tremuloides*) (Boese, 2003). The D-covers were used by Elshorbagy et al. (2007) to develop the site-specific SDW model. The second study area is the Hill top site, a flat reclamation landform located adjacent to the D-covers with an approximate area of 2 km². Hill top site was constructed

in 2001 of 0.2 m of peat/mineral mix overlying 0.8 m of till. Both the D-covers and Hill top site are located on South Bison Hill. The major plant species on the Hill top study area are foxtail barley (*Hordeum Jubatum*), and minor species include fireweed (*Epilobium angustifolium*) (Parasuraman et al., 2007). The third site is the South West Sand Storage (SWSS), which was constructed of 0.2-0.4 m of Till/secondary cover material over 1.0 m of tailings sands. It is currently the largest operational tailings dam in the world, approximately 40 m high and a 20H:1V side slope ratio. The vegetation varies with groundcover including horsetail (*Equisetum arvense*), fireweed (*Epilobium angustifolia*), and white and yellow clover (*Melilotus alba*, *Melilotus officinalis*). Tree species include Siberian larch (*Larix siberica*), hybrid poplar (*Populus sp. hybrid*), trembling aspen (*Populus tremuloides*), white spruce (*Picea glauca*) and willow (*Salix sp.*) (Parasuraman et al., 2007).

An intensive hydrological and meteorological measurement program is carried out on these experimental sites to monitor the evolution of the reconstructed watersheds. The hydrological variables include the matric soil suction, volumetric moisture content (measured bi-daily using TDR and soil suction sensors at different depths), and soil temperature of different soil layers, measured on hourly basis for the corresponding soil moisture measurement depths. Additional monitored variables include runoff and interflow. Measurements of the latent heat fluxes are made with the eddy covariance technique (EC) and reported in 30-min interval (Carey, 2008). A weather station is used to provide hourly meteorological measurements of air temperature (AT), precipitation (P), net radiation (NR), water vapour gradients and other meteorological variables. More

details on the field instrumentation and monitoring program can be found in Boese (2003), Julta (2006) and Carey (2008). Based on the climate data from an Environment Canada meteorological station at Fort McMurray ($57^{\circ}2.4'N$ and $111^{\circ}33.6'W$), a 30-year period (1971-2000) the mean annual temperature is $0.7^{\circ}C$, and the mean annual precipitation is 455.5 mm. The soil properties are as follows: the saturated hydraulic conductivities are 408 (cm/day), 50.4 (cm/day), and 0.72 (cm/day), and the porosity values are 0.5, 0.54, 0.25 for peat, till and shale, respectively (Elshorbagy et al., 2005).

2.5.2 Natural Watersheds

The GSDW model is used to simulate the hydrological performance of a natural watershed to validate its capability in capturing the dynamics of the various water balance components in undisturbed systems. The old aspen (OA) forest site, part of the former Boreal Atmosphere Exchange Study (BOREAS), is considered in this study as it is climatically similar to the Fort McMurray region. The OA site is, roughly 1580 Km^2 , located near the south end of Prince Albert National Park, Saskatchewan ($53.629^{\circ}N$, $106.198^{\circ}W$). Because of the relatively flat topography and the homogeneity of vegetation, as well as the semi-arid climate, the site is modeled as a lumped unit or column of soil. The field instrumentation of the OA site has been providing continuous measurements since 1997 as part of the Boreal Ecosystem Research and Monitoring Sites (BERMS) program (<http://berms.ccrp.ec.gc.ca>). The soil is a well drained loam to clay loam. The top 0.1 m layer is an organic layer (leaf litter, plus fermentation layer); 0.07-0.3 m of till mixed with sand and clay, a 0.45 m layer derived from gravelly and clay enriched till, overlying, a mixture of sandy clay loam of 0.40 m. The soil properties are as

follows: the saturated hydraulic conductivities are 25 (cm/day), 5.76 (cm/day), and 4.8 (cm/day), and the porosity values are 0.51, 0.45, 0.46 for A, B and C horizons, respectively (Cuenca et al., 1997). The forest canopy is dominated by trembling aspen (*Populus tremuloides*) with an average height of 21 m and about 2 m high hazelnut (*Corylus cornuta*) understory interspersed with alder (Balland et al., 2006). AT and P data are collected at 30-min intervals. Based on the data from an Environment Canada meteorological station nearby Waskesiu Lake (53.92° N, 106.07° W), the mean annual precipitation was 467 mm.

Thermocouple sensors recorded soil temperature every 30-min at 0.02, 0.05, 0.10, 0.20, 0.50 and 1.00 m below the moss layer (organic layer). CS615 soil moisture sensors (TDR) were used to measure the volumetric moisture content of the soil at 0.08, 0.23, 0.45, and 1.05 m below the ground surface. Net radiation was measured using a Kipp and Zonen CNR-1 net radiometer above the canopy. Measurements of the latent heat fluxes were made with the eddy covariance technique (EC) and reported with 30-min interval. LAI was measured near the flux tower using a plant canopy analyzer (PCA) (model LAI-2000). For the purpose of integrating the extracted data into the GSDW model, all the data were aggregated to a daily time-step. Additional information for the OA site can be obtained from Cuenca et al. (1997).

The values of total precipitation for the D-covers, and the SBH site are 341.2 mm and 294.3 mm for years 2005 and 2006, respectively. For the SWSS site, the value of total precipitation is 285.9 mm, and 366.3 mm in the years 2005 and 2006, respectively.

Finally, the corresponding values for the OA site were 479 mm, and 483.7 mm in the years 1999–2000, respectively.

The main objective for this study was to develop a generic system dynamics model to simulate different hydrologic processes in disturbed and undisturbed watersheds, and various reconstructed sites were simulated to evaluate the model performance over a variety of different reclamation strategies. The model was applied to inclined watersheds, as in the case of the D-covers and the SWSS sites, to horizontal terrain, as in case of the SBH and OA sites, and on a set of different soil layers with a variety of thicknesses and soil stratifications.

2.6 Results and Analysis

The goodness-of-fit between the measured and simulated datasets are generally quantified using multiple performance indicators, providing different aspects of comparison. This paper uses the root mean square error (RMSE), the mean absolute relative error (MARE), the percent of error measurement in the peak (PEP), and the correlation coefficient (R) as the main performance indicators, in addition to visual comparison. Both RMSE and MARE are overall error measures, where RMSE is a real value metric and MARE a relative value metric. The RMSE is biased towards high values, while the MARE is less sensitive to high values as it does not square the error magnitude (Dawson et al. 2007). Due to these limitations, R is used as a complementary error measure that quantifies the overall agreement between the observed and predicted values. PEP focus on the peaks values, yet not to the overall agreement between the two

datasets. It comprises the difference between the highest values of observed and simulated datasets, made relative to the magnitude of the highest values in the observed dataset and expressed as a percentage and for a perfect model the PEP value is zero.

As mentioned, the traditional realm of hydrologic models has been the prediction of rainfall-runoff process. These predictions are used in flood warning systems, navigation, water quality management and many water resource applications. However, land reclamation concentrates on replicating the performance of natural watersheds in terms of supporting vegetation growth. Consequently, it is crucial to simulate hydrological processes that directly impact the ecological function of the watershed. As a result, the calibration of the GSDW model was performed based on two hydrological processes connected with the ecological function of the reconstructed watersheds: soil moisture and actual evapotranspiration (AET). Calibration was performed by setting individual parameter values and executing a series of simulations. This process was repeated (trial and error) until no further improvement in the values of the error measures and the visual match between simulated and observed AET could be attained. Table 2-1 lists the calibration parameters used on the different study sites together with their corresponding values. The calibration of the GSDW model indicates sensitivity to the lambda coefficients (λ_n), a main factor in the AET equations, and the infiltration coefficients (I_{cn}), which directly affect the moisture distribution in each layer.

Table 2-1 Calibration parameter values for the developed GSDW model

Parameter	D1	D2	D3	SBH	SWSS	OA
Infiltration coefficient (I_{c1}) (<i>dimensionless</i>)	0.004	0.008	0.08	0.003	0.02	0.003
Infiltration coefficient (I_{c2}) (<i>dimensionless</i>)	0.003	0.004	0.002	0.002	0.002	0.002
c_i^a (<i>dimensionless</i>)	6	6	6	4	6	4
C_1^b (mm/day ⁰ C)	0.22	0.45	0.35	0.15	0.35	0.1
C_2 (mm/day ⁰ C)	0.16	1.7	0.03	0.1	2.1	1.9
C_3 (mm/day ⁰ C)	0.02	0.1	0.02	0.09	0.02	0.09
Interflow coefficient (C_I) (<i>dimensionless</i>)	0.3	0.3	0.3	-	0.3	-
Lambda ^c (λ_1) (<i>dimensionless</i>)	5.15	3.15	3.15	2.7	3.95	1.6
Lambda (λ_2) (<i>dimensionless</i>)	1.1	0.3	1.3	1.9	0.9	2.9
Lambda (λ_3) (<i>dimensionless</i>)	0.2	0.2	0.3	0.3	0.2	0.3
Melt factor (<i>dimensionless</i>)	0.7	0.6	0.7	0.5	0.7	0.6

^a c_i is an exponent describing the influence of TI on soil defrosting; ^b c_i evapotranspiration constant (mm/day⁰C) from the (1st) layer; ^c λ_i is an exponential coefficient, used to calculate the AET, modified from the SDW to be temperature dependant.

The terrestrial ecology community over the last two decades has developed models to simulate various hydrological processes. Operational applications are demanding, as they request both efficiency and robustness. Therefore, there is always a debate of the modeling approach that should be selected; model choices must be justified through extensive testing and for robustness considerations, where simple models must be preferred over more complex models when they are of equal efficiency. The next section compares the performance of the GSDW model with the Soil and Water Assessment Tool (SWAT), a widely used hydrological model.

2.6.1 SWAT model

SWAT is a basin-scale, continuous-time model created in the early 1990s that operates on a daily time step and is designed to predict the impact of management on water, sediment, and agricultural chemical yields in ungauged watersheds (Arnold and Fohrer, 2005). The model is physically based and capable of continuous simulation over long time periods. SWAT components include weather, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, bacteria, pathogens, and land management. In SWAT, a watershed is divided into multiple sub-watersheds, which are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, and soil characteristics. Climatic inputs used in SWAT include daily precipitation, maximum and minimum temperature, solar radiation data, relative humidity, and wind speed data. The overall hydrologic balance is simulated for each HRU, including canopy interception of precipitation, partitioning of precipitation, snowmelt water, redistribution of water within the soil profile, evapotranspiration, lateral subsurface flow from the soil profile, and return flow from shallow aquifers. Moreover, bypass flow can be simulated, as described by Arnold et al. (2005), for soils characterized by cracking. SWAT has proven to be an effective tool for assessing water resource and nonpoint-source pollution problems for a wide range of scales and environmental conditions across the globe (Arnold et al., 1998; Arnold and Fohrer, 2005). Moreover, SWAT's open source code allows modellers to modify and add to the model code in an interactive way.

SWAT was manually calibrated from 2000 to 2005 and validated for 2006, for D2 and D3 covers. The authors performed a manual sensitivity/calibration analysis of 12 SWAT input parameters, which showed that saturated hydraulic conductivity, plant uptake compensation factor (EPCO) and soil evaporation coefficient (ESCO) were the most sensitive parameters that affected the simulation results. In the current study, both watersheds are considered one hydrologic response unit (HRU) that consist of homogeneous land use, management, and soil characteristics. Table 2-2 presents SWAT model performance indicators with regards to its ability to simulate the soil moisture content for D2 and D3 covers. In general the GSDW model results, presented in Table 2-2 **Error! Reference source not found.**, rival the SWAT model in the performance, particularly for the top layer. However, SWAT performance in the subsequent layer was slightly better. Figure 2-3 shows the soil moisture dynamics for the D3 cover. SWAT was capable of simulating the snowmelt period better than the GSDW model, which may be attributed to the fact that SWAT was capable of simulating bypass flow. In contrast, the GSDW was able to reproduce the soil moisture dynamics during the growing season in the upper layer (which is the most important layer for vegetation) superior to SWAT. Cumulative AET-values were overestimated using SWAT by 17% and 15% for D2, and D3, respectively.

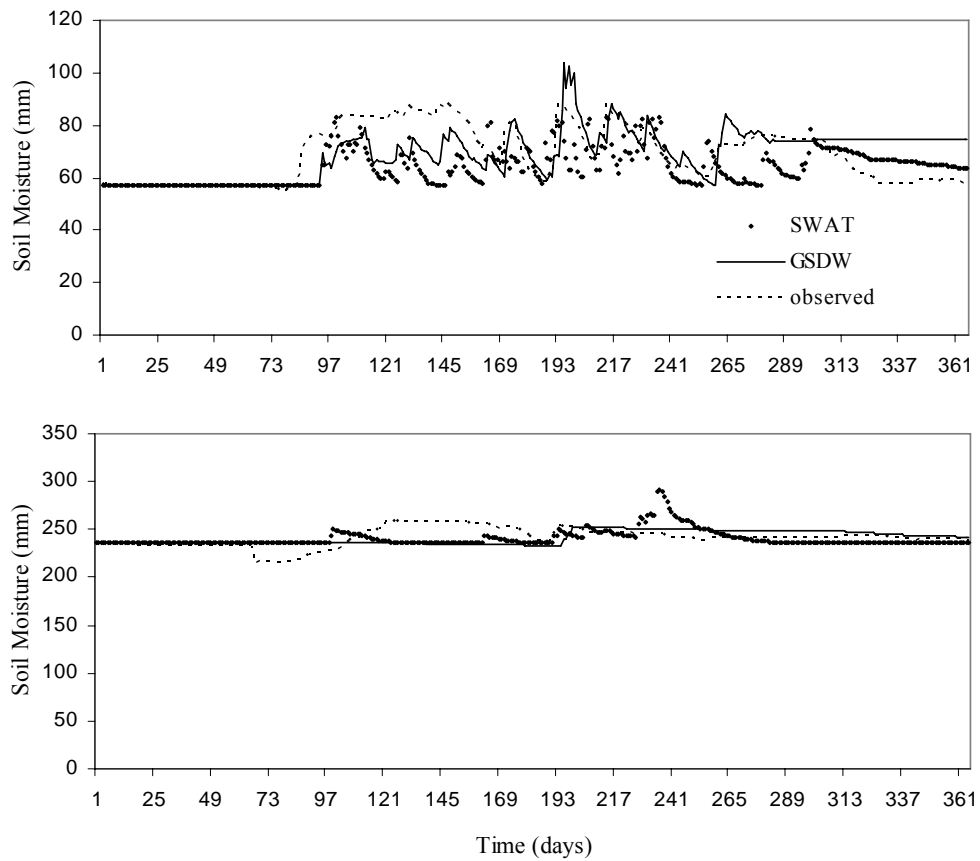


Figure 2-3 Simulated and observed moisture dynamics in the D3 cover for validation year 2006 using both SWAT and GSDW models; (a) peat layer; (b) till layer.

2.6.2 Simulation results of the GSDW model

As the GSDW model is an advance on the pre-existing SDW model, preliminary runs were made to validate the model performance. First, the SDW model was recalibrated for 2005 and validated on cover D3 for 2006. The SDW model MARE were 16% and 6% for validation year compared to the GSDW model values of 8% and 6% for peat and till, respectively. The RMSE for the SDW model were 13.5 and 17.3 mm, whereas, 3.1, 4.3 mm for the GSDW model, for peat and till, respectively. The simulated cumulative AET were 253 and 283 mm for the validation year, for the SDW and the

GSDW models respectively, compared to 276 mm of measured AET. The results presented in Table 2-2 show that the model performance with regards to the D3-cover was superior to the preliminary run for the site-specific SDW model built for the D-covers by Elshorbagy et al. (2005). A second attempt was made to recalibrate the GSDW model to simulate the moisture dynamics of D1-cover and compare the results to the findings by Elshorbagy et al. (2007). Therefore, 2001 and 2002 were chosen as calibration and validation years, respectively. The MARE values of the GSDW model were 7% and 8.2%, and the RMSE values were 4.3 mm and 7.0 mm for peat and till layers, respectively. The previous values were compared to MARE of 9% and 11%, and RMSE of 7.0 and 9.0 mm for peat and till layers, respectively, for the SDW model. The improvement in model performance was mainly attributed to implementing the canopy interception module to the GSDW model. Table 2-2 lists the GSDW model performance indicators with regard to its ability to simulate the soil moisture content of the study areas. For the SBH, SWSS and OA sites, the model provided satisfactory results, the RMSE values ranged between 2.5-4.8 mm, which indicates that the average error was not more than ± 5 mm away from the mean soil moisture value.

Table 2-2 Performance statistics of the GSDW and the SWAT models regarding soil moisture

Model	Site	Layer	Year	MARE (%)	RMSE (mm)	R	PEP
GSDW	D1 ^a	Peat	2005	7	2.9	0.83	
			2006	13	3.5	0.30	-8.1
		Till	2005	2	1.5	0.32	
			2006	7	2.7	0.62	-13
	D2 ^a	Peat	2005	18	3.8	0.44	
			2006	14	3.4	0.42	-12
		Till	2005	26	4.1	0.33	
			2006	29	4.4	0.10	-27.6
	D3 ^a	Peat	2005	11	3.3	0.77	
			2006	8	3.1	0.57	-2.4
		Till	2005	2	2.4	0.4	
			2006	6	4.3	0.22	8.6
	SBH ^a	Peat	2005	9	3.0	0.71	
			2006	6	2.5	0.59	-7.3
		Till	2005	3	2.9	0.49	
			2006	5	4.0	0.35	-6.8
	SWSS ^b	Till	2005	6	3.3	0.70	-12.7
			2006	6	3.1	0.71	
		Tailing sand	2005	7	4.1	0.76	4.3
			2006	6	3.9	0.57	
	Old Aspen ^c	A-Horizon	1999	9	2.8	0.69	-
			2000	7	2.8	0.87	
		B-Horizon	1999	10	4.4	0.87	-20.7
			2000	5	3.1	0.16	
SWAT ^d	D2	Peat		19	14	0.01	
		Till	2006	8	6	0.2	
	D3	Peat		16	4.2	0.1	
		Till	2006	5	5.4	0.33	

^a Calibration year 2005; validation year 2006; ^b Calibration year 2006; validation year 2005; and

^c Calibration year 2000; validation year 1999; ^d validation year 2006.

The moisture dynamics of the thinnest soil cover (D2) had a flashy response compared to the other two D-covers. The R statistic indicated that the GSDW model captured the general trend of the soil moisture in particular for the surface peat layer where R ranges from 0.30 to 0.77 in the validation phase. The subsurface till layer of the D2-cover showed a relatively low correlation of 0.10, whereas the SWSS site showed negative correlation coefficient, which is attributed to the high spatial variability of the soil moisture measurements in the reconstructed watershed, as well as the effect of the depth- averaging for the observed values of soil moisture. For the overall water balance, these errors are very small in terms of water depth (mm). The simulated soil moisture dynamics of the surface and subsurface soil layers are shown in Figure 2-4, Figure 2-5, and Figure 2-6 for the SWSS, SBH, and the natural old aspen watersheds, respectively. For the three figures, in the winter period, there was no significant dynamics for the moisture content because soil during this period was frozen and the model behaved accordingly. As cited by Boese (2003), the sensors used for the measurement of soil moisture at the study sites were not operating reliably during the frozen conditions; also, the AET values should be neglected during the winter season. Therefore, the evaluation of the soil moisture behaviour in the winter season is not significant and may mislead the analysis of the model results. Therefore, only the values of the growing season are considered.

As the air temperature reaches active threshold value, snow starts melting and liquid water infiltrates into the soil layers. A sudden increase of moisture content ensues once the surface layer is thawed and corresponds to the amount of snow that is

accumulated when the temperature was below zero. After the snowmelt period, soil moisture in the surface layer fluctuates due to the variation of rainfall intensity and evapotranspiration. This period lasts until the temperature falls down below the active air temperature and the soil starts refreezing again in the fall. Figure 2-4, Figure 2-5, and Figure 2-6 show consistencies of soil moisture patterns related to corresponding rainfall events. The surface layer storage component was responsive to rainfall events, whereas the responses of the subsurface layers were not as rapid. In general, the results indicated that the simulated soil moisture patterns were similar to the observed patterns.

The PEP measurement was applied to the results of the model and presented in Table 2-2. The negative sign indicates an over-estimate of the peaks in the simulated runs whereas the under-estimate produces a positive sign. There are several recorded increases in the observed soil moisture at the SWSS site when the soil was frozen (Figure 2-4). This could be attributed to an error in the measurement or contribution of preferential flow to the soil pores. Figure 2-5 and Figure 2-6 show increases in the simulated soil moisture storage in the 2nd layer during the summer period for both SBH (year 2006) and OA (year 1999). This sudden increase is correlated with rainfall events of 41 mm and 60 mm, respectively. During immense rainfall events, the increase in the soil moisture storage is due to the restriction on the lateral subsurface flow movement in flat landscapes.

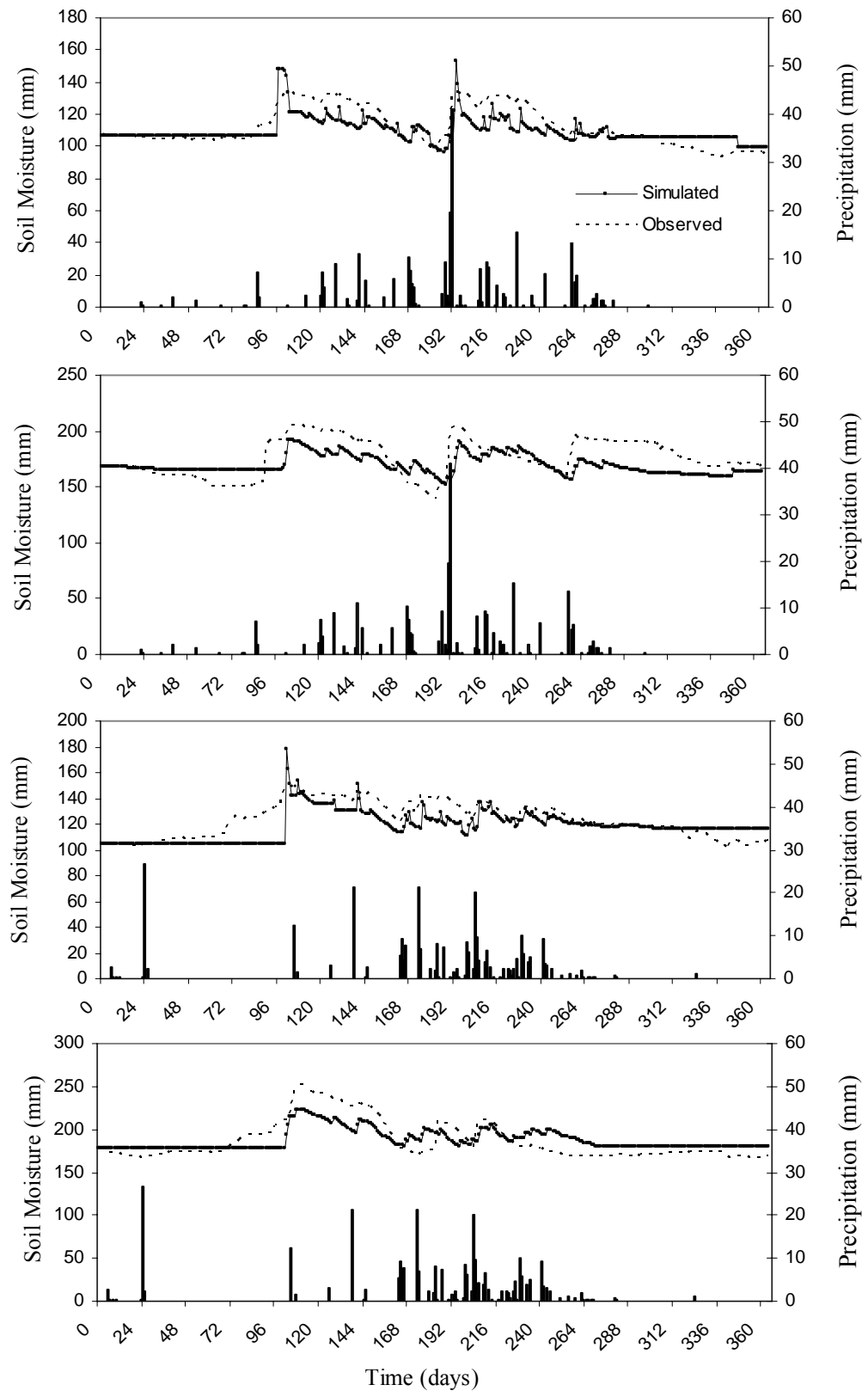


Figure 2-4 Simulated and observed moisture in the SWSS watershed; (a) Till layer calibration (2006); (b) Tailings sand layer calibration (2006); (c) Till layer validation (2005); (d) Tailings sand layer validation (2005).

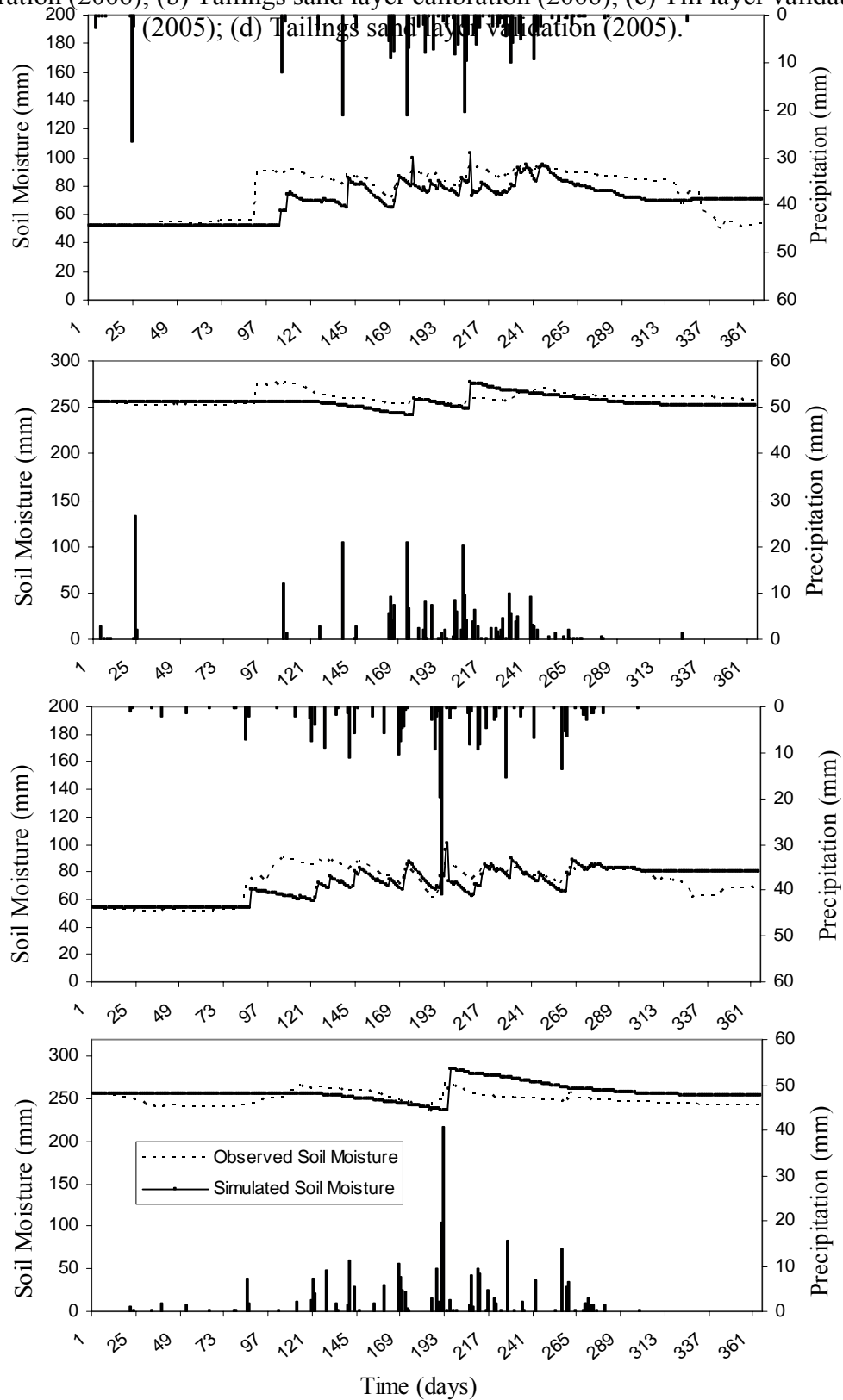


Figure 2-5 Simulated and observed moisture in the SBH watershed; (a) Peat layer calibration (2005); (b) Till layer calibration (2005); (c) Peat layer validation (2006); (d) Till layer validation (2006).

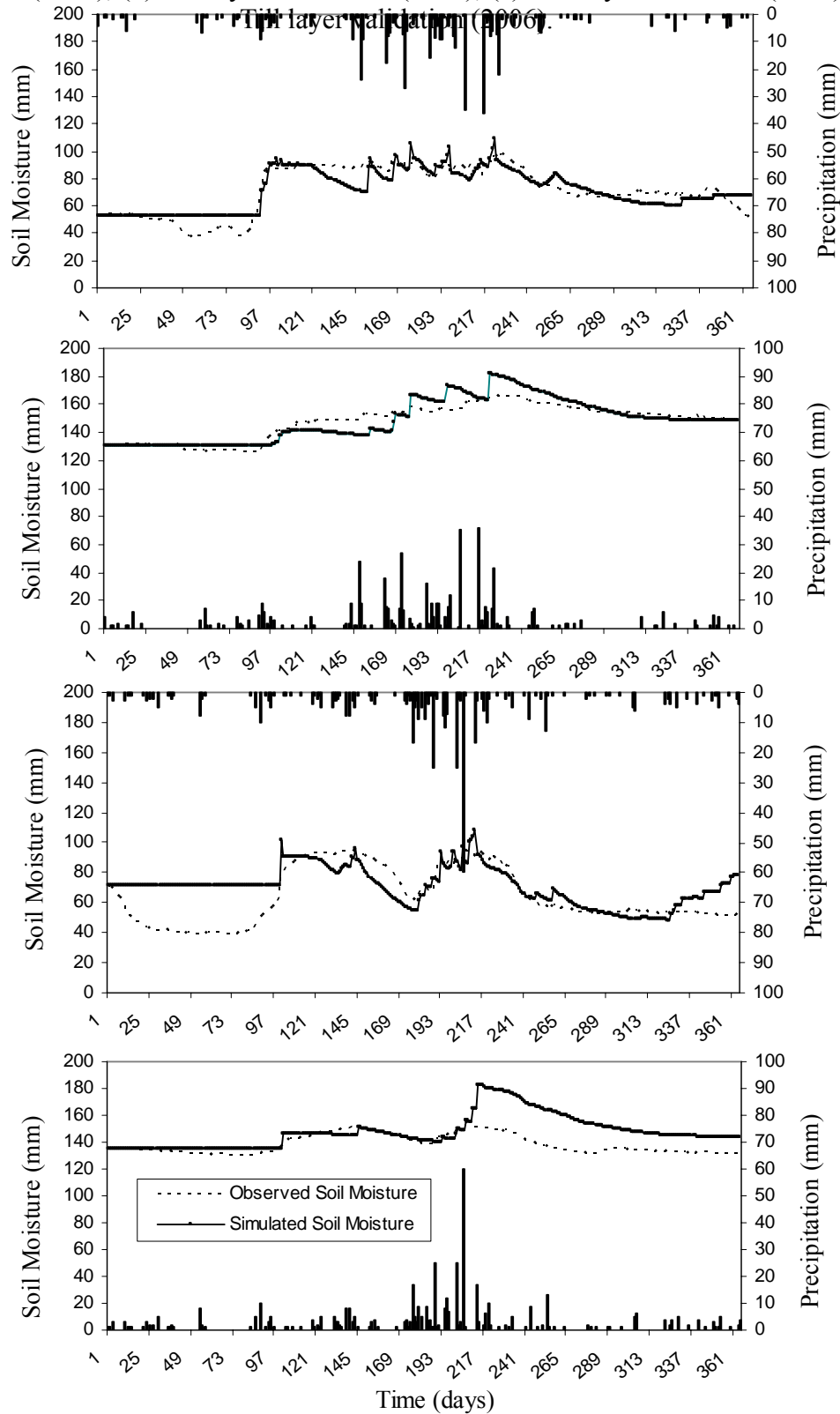


Figure 2-6 Simulated and observed moisture in the Old Aspen watershed; (a) A-Horizon calibration (2000); (b) B-Horizon calibration (2000); (c) A-Horizon validation (1999); (d) B-Horizon validation (1999).

Figure 2-7 presents the cumulative AET over the growing season period for the validation years measured using the EC versus the simulated AET values. The graph presents an overall agreement of the observed and the simulated cumulative AET for the three sites, in both magnitude and trend. The reasonable match between measured and simulated AET values provide another indication of the ability of the GSDW model to capture the dynamics of the hydrological processes in the reconstructed and the natural sites. The model slightly overestimated the cumulative AET fluxes in the natural OA sites, where the measured AET values using the EC method was 338 mm and the simulated was 365 mm. The GSDW model under-estimated cumulative AET fluxes for SWSS site, where values were 319 mm and 312 mm, for observed and simulated, respectively. For the SBH site, the GSDW model underestimated cumulative AET values, with a measured cumulative AET of 276 mm and a simulated AET flux of 261 mm. The error between the measured and simulated cumulative AET values for the SWSS, SBH, and the OA sites were 2%, 5%, and 8%, respectively. Figure 2-8 shows observed and simulated daily AET at SWSS, SBH, and OA, respectively, where the model simulated daily AET flux relatively good.

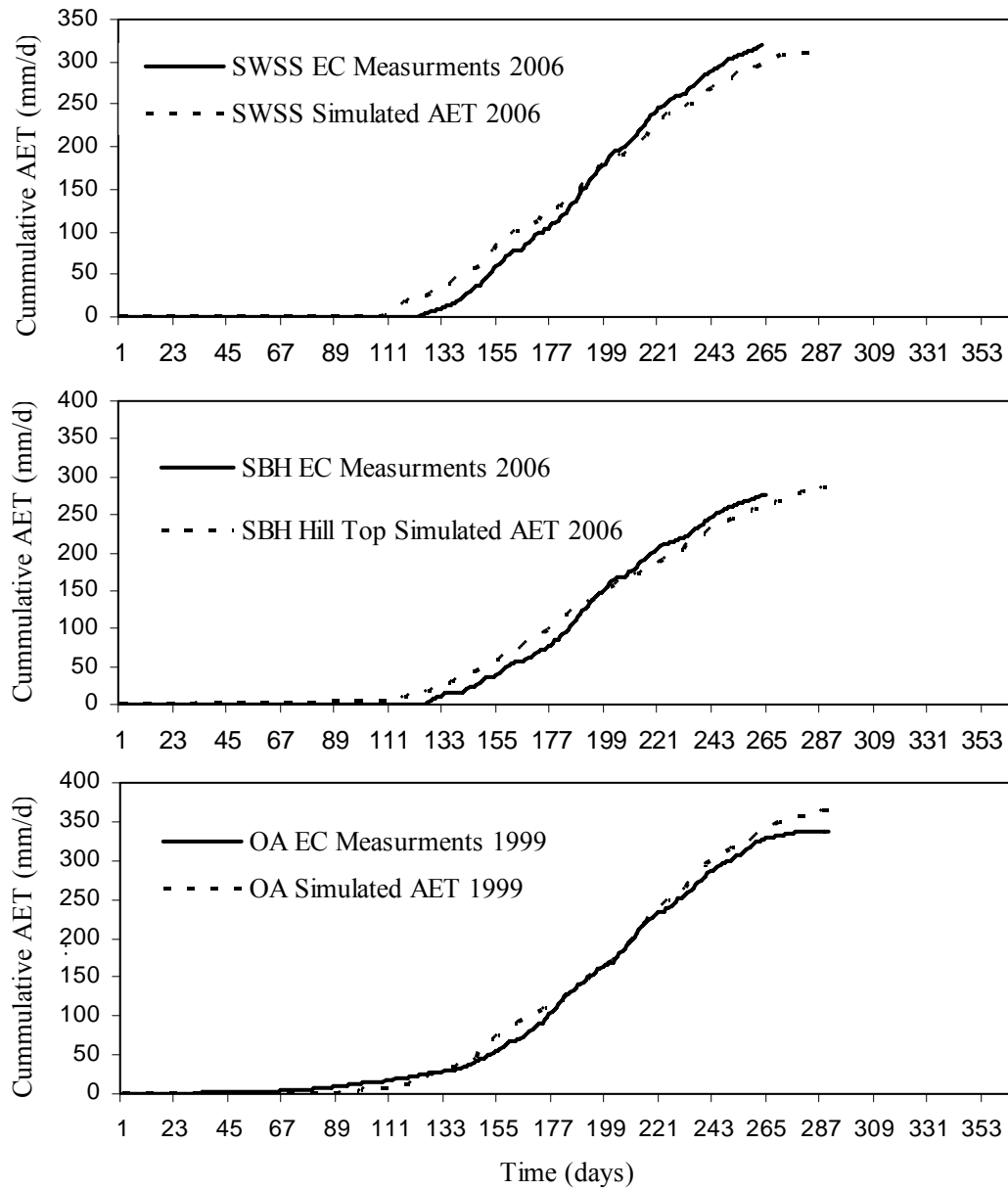


Figure 2-7 Simulated and observed actual cumulative evapotranspiration for; (a) SWSS; (b) SBH; (c) OA sites, respectively.

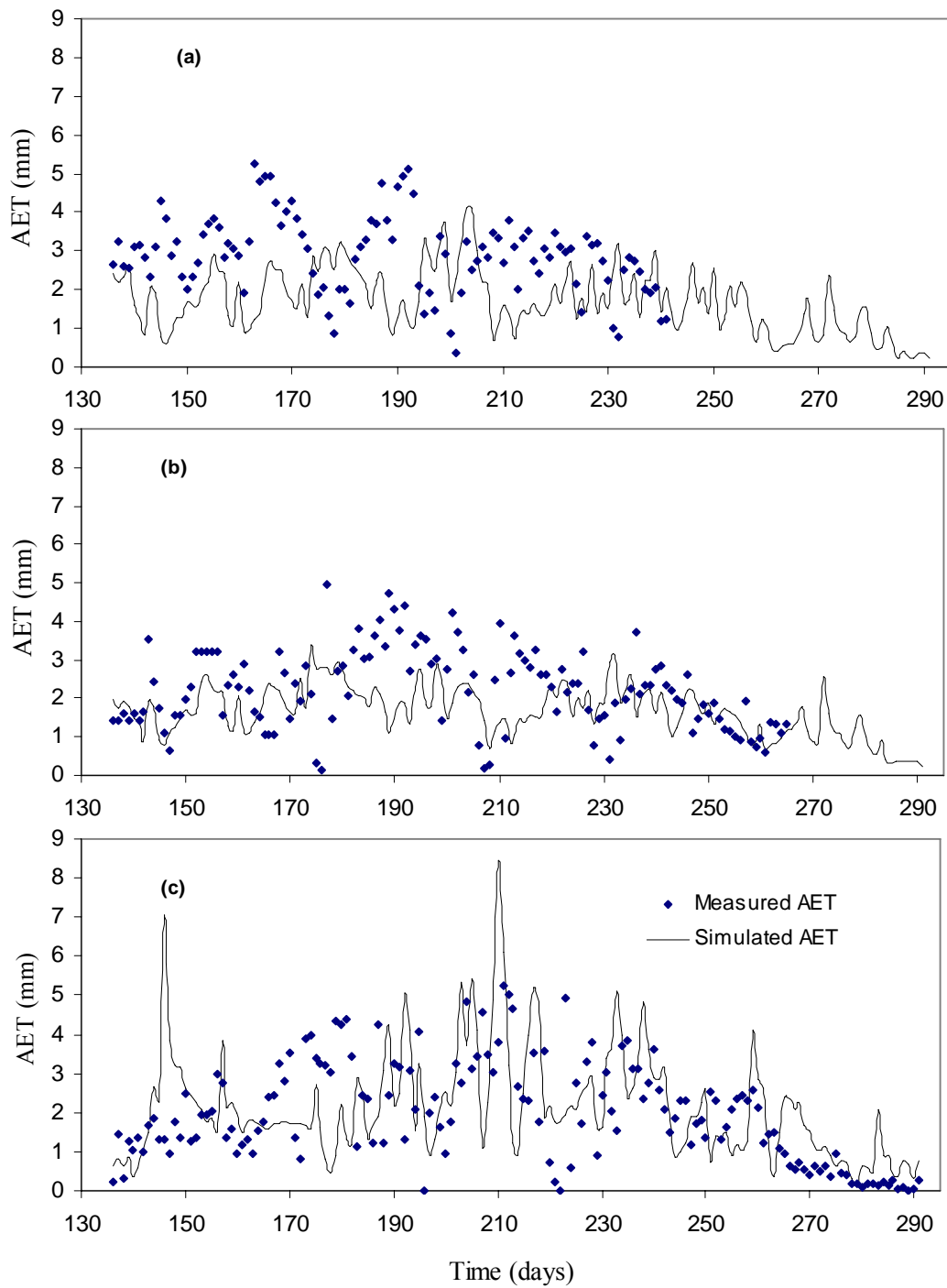


Figure 2-8 Simulated and Observed daily AET values for the growing season period; (a) SWSS; (b) SBH; (c) OA sites.

Table 2-3 shows the performance statistics of the GSDW model for the SWSS, SBH, and OA sites. The model provided the RMSE values of 1.22, 1.16, and 1.49 mm, respectively, whereas the R statistics were 0.60, 0.35, and 0.38. In general, the performance statistics of the cumulative annual AET values during the growing season were better compared with the daily AET values.

Table 2-3 Performance statistics of the GSDW model regarding daily AET flux

Site	Year	RMSE (mm)	R
SWSS	2005	1.42	0.60
SBH	2006	1.18	0.37
OA	1999	1.49	0.38

Mainly, reconstructed covers, e.g. the inclined D-covers, were designed to act as a sponge, regarding store and release abilities. The top layer was selected having a high hydraulic conductivity to increase infiltrated surface water in to the soil matrix and minimizing runoff generation, and redistribute the trapped liquid water to the subsequent layer to reduce evaporation. The subsequent layer is relatively fine textured with clay particles dominating the soil, the clay content reduce the hydraulic conductivity and at same time allows for high porosity to allow for storing more moisture for the growing season. Figure 2-9 shows the observed and simulated overland flow for the inclined D1 cover for 2001, where the model triggered some runoff during snowmelt period.

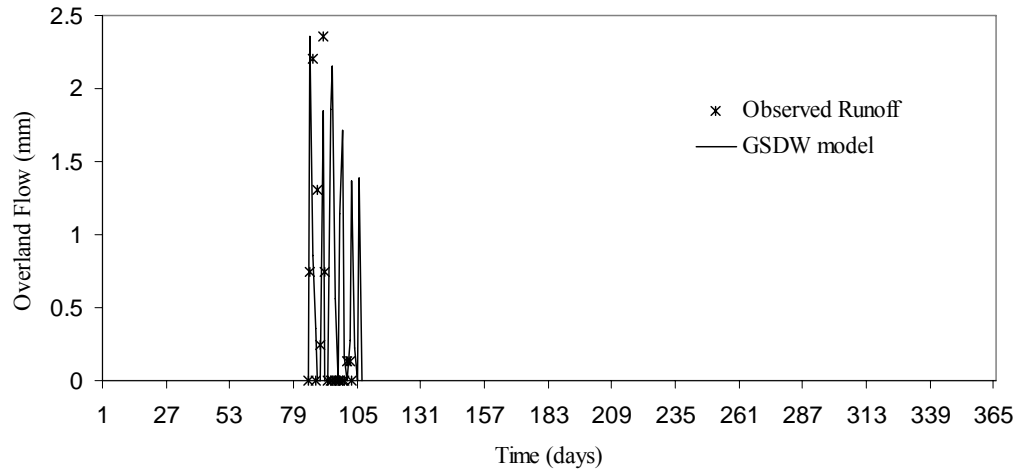


Figure 2-9 Simulated and Observed Runoff (overland flow) of the D1 cover in 2001.

The annual water balance components, during validation periods, were simulated by the GSDW model and are summarized in Table 2-4. The intercepted precipitation from implementing the canopy module ranged from 4% to 15% of the total precipitation, runoff varied from 0.5% to 5% of the total precipitation, and ET ranged from 78% to 98% of the total precipitation. The difference between precipitation as input, AET, interception, and runoff as outputs is the percolated water to subsequent layers.

Table 2-4 Annual water balance components for the validation years

Site	Total Precip. (mm)	Intercepted Precip. (mm)	Net Precip. (mm)	AET (mm)	Runoff (mm)
D1	294.3	19.45	274.85	280	14.25
D2	294.3	25.5	268.8	271	11.51
D3	294.3	29.49	264.81	283	8.78
SBH	294.3	23.65	270.65	261	14.14
SWSS	366.3	16.1	351.2	312	9.72
OA	479	75.92	403.08	365	2.0

2.7 Discussion

Many hydrological models are able to represent hydrological processes at the watershed scale, but the majority with high parameter requirements. Therefore, there is a need for a tool that facilitates the simulation of the response of various soil cover designs and to evaluate their performance relying on widely available data. During the preliminary stages of the watershed development, soil moisture plays the key role in vegetation growth, especially in the root zone layers (Kilmartin, 2000). The GSDW model is able to simulate the soil moisture response with a good accuracy of less than 5 mm, on average, from observed values. Previous efforts of simulating similar sites resulted in agreement between the observed and simulated values in trend only, not in magnitude. For example, Balland et al. (2006) modelled the snow pack, soil temperature, and soil moisture in the OA site, and achieved agreement between the measured and simulated snow pack and soil temperature, yet for soil moisture, the agreement was in trend not in magnitude. They attributed this difference in model performance to local conditions and sensor surroundings, in addition to different uncertainties associated with the modelling procedure itself.

The preliminary runs showed that the GSDW model surpasses the previous SDW model in performance, which may be attributed to the introduction of the canopy interception module in the model structure. The GSDW and SWAT preliminary runs showed a comparable performance. SWAT has the ability of subdividing a watershed into hydrologic response units (HRUs), which gives the model credibility in simulating large watersheds. In the current study, both reconstructed watersheds were considered as

a single homogeneous hydrologic response unit, and the simulation was conducted using a set of lumped data. The trial and error procedure, which was implemented during the model calibration, in conjunction with the previous assumptions, reduced SWAT abilities in simulating soil moisture dynamics. The aim of comparing SWAT and GSDW models was to supply the modeller with an idea of which model to use based on a set of lumped data. The use of complex physically based models, such as SWAT with lumped inputs, is neither effective nor economic. The GSDW model has a simpler structure, with less number of calibrated parameters, and relies on widely available meteorological data.

Evapotranspiration is a key process for water resources management, particularly in arid regions. AET depends on a large variety of factors: vegetation, soil type, topography, and the meteorological conditions. The rate of evapotranspiration is largely controlled by available energy and available soil moisture. Soil and climatic variables control vegetation dynamics, while in return vegetation modulates the water balance by acting as an intermediate link between soil and the atmosphere. Soil moisture and vegetation affect the thermal inertia and shortwave albedo of the surface. Furthermore, numerous studies support the assertion that in arid and semi arid regions, soil moisture flux is the key variable in soil-vegetation-atmosphere continuum (Rodriguez-Iturbe, 2000; Rodriguez- Iturbe et al., 2001; Porporato et al., 2001). Weeks and Wilson (2006) conducted a study to predict the surface water balance for constructed soil covers on waste disposals. The study showed that the slope direction and angle can have a significant effect on the net radiation received by the slope, and hence affect evaporation predictions. As a result of the assumptions associated with the model

structure, the daily evapotranspiration is simply correlated to moisture availability without relying on other influencing variables, e.g., characteristics of the surrounding environment and type and condition of vegetation, which in turn affects the daily AET simulations. The EC method, which is used as a direct measurement of AET, has an accuracy range from ± 15 to $\pm 20\%$ for hourly evapotranspiration measurements and up to ± 8 to $\pm 10\%$ for longer periods (Eichinger et al., 2003; Strangeways, 2003). However, the GSDW model managed to simulate the cumulative annual AET to a very reasonable accuracy, less than $\pm 8\%$ of the annual measured AET value, with minor overestimation and underestimation periods.

Generally, three sources of uncertainties in the modeling process can be distinguished: errors in input variables, model assumptions and parameterization, and algorithms of process description. To visualize one type of uncertainty associated with errors in the input variables, Gee and Hillel (1988) pointed out that precision in precipitation is seldom less than $\pm 5\%$. The spatial and temporal variability of soil physical properties within the same site adds an extra level of uncertainty to the measured data. The required characteristic of the soil physical properties for the GSDW model, such as the saturated hydraulic conductivity and the pore size distribution, are subject to high degree of spatial and temporal variability (particularly in reconstructed soil covers). The saturated hydraulic conductivity in the reconstructed D-covers, e.g., increased by 400% from 2000 to 2001, as tabulated by Elshorbagy et al. (2007). All models are limited to the extent that the parameterizations of physical processes are only approximations of the true soil physics and vegetation physiological action. Therefore, a long monitoring

period for reconstructed watersheds is essential, and is suggested by Rick (1995) to be seven years. This monitoring period will allow tracking of different changes and evolution encountered in reconstructed watersheds.

There were no daily observed values for the canopy losses to compare the model results, however, the adopted approaches for calculating the interception loss were validated in several previous studies. Moreover, testing other components of the water balance implicitly validated the interception component. The GSDW model does not account for macropores. Nevertheless, flow in macropores may play an important role for soil water fluxes. The soil moisture predictions during snowmelt in some case studies are not well represented, which could be attributed to the deficiency in representing the flow of water through macropores. During the snowmelt period and while the soil is still frozen, melted snow tends to bypass into soil layers through the macropores, giving a sudden increase in soil moisture. Further improvement to the GSDW model could be achieved by incorporating macropore flow, enhancing soil moisture simulation and consequently other hydrological processes. The model shows sensitivity to AET and infiltration coefficients-related calibration parameters, which confirm that AET process and soil moisture content, play the dominant role in simulating the hydrological performance of the watersheds.

2.8 Conclusions

This study presents a generic system dynamics watershed (GSDW) model. GSDW is a simple, reliable, and comprehensive tool that facilitates hydrological

simulation, and thus the assessment of the sustainability of various reconstructed watersheds. It is a lumped conceptual model capable of simulating various components of watershed hydrology. The model uses sets of meteorological, vegetation, and hydrological data to evaluate different hydrological processes on a daily basis. The validity of the proposed model was assessed by evaluating the predicted soil moisture redistribution, and actual evapotranspiration in different sites reasonably well in trend and in magnitude. The simulation results showed that the model performance with regard to the D-covers was quite comparable to the findings of Elshorbagy et al. (2005; 2007), with considerable improvements in soil moisture simulation. For the three case studies, the model provided good results, based on the three selected performance measures. Spatial and temporal variability of the soil moisture measurements and the depth-averaging procedure affected the values of the performance measures, and consequently the overall assessment of the GSDW model. However, the simulated soil moisture showed consistent behaviour with the different rainfall events, which verifies the validity of model results. As expected, GSDW model results indicated the sensitivity of the top layer to rainfall events and other meteorological conditions, compared to the trimmed effect on the response of the subsurface soil layers. Generally, the GSDW model was capable of capturing the dynamics of the various water balance components in both reconstructed and natural watersheds. The canopy interception module, which is the main upgrade from the SDW model, allows the GSDW model to simulate the future performance of the reconstructed watersheds and long term climate scenarios. Furthermore, it allows users to compare different vegetation alternatives for future reclaimed covers. The developed GSDW model provides a vital tool, which enables the investigation of the utility of

different soil cover alternative designs, hypothetical covers, and evaluation of their performance. Also, it facilitates further probabilistic analysis and scenario analysis, which provides the mining industry with a comprehensive decision support tool.

2.9 Acknowledgements

The authors acknowledge the financial support of NSERC through its Discovery Grant and CRD programs, and the University of Saskatchewan's devolved scholarship program. The financial and the in-kind contribution of Cumulative Environmental Management Agency and Syncrude Canada Ltd., are also appreciated.

2.10 References

- Arnold J.G. and N. Fohrer, 2005. SWAT2000: Current capabilities and research opportunities in applied watershed modeling. *Hydrological Processes*, 19(3):563-572.
- Arnold, J.G., K.N. Potter, K.W. King and P.M. Allen, 2005. Estimation of soil cracking and the effect on surface runoff in a Texas Blackland Prairie watershed. *Hydrological Processes*, 19(3):589-603.
- Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams, 1998. Large area hydrologic modeling and assessment: Part I. Model development. *Journal of American Water Resources Association*. 34(1):73-89.

- Arora, V., 2002. Modeling vegetation as a dynamic component in soil-vegetation-atmosphere transfer scheme and hydrological models. *Reviews of Geophysics*, 40, 1006, doi:10.1029/2001RG000103.
- Balland, V., J. Bhatti, R. Errington, M. Castonguay and P. A. ARP, 2006. Modeling snowpack and soil temperature and moisture conditions in a jack pine, black spruce and aspen forest stand in central Saskatchewan (BOREAS SSA). *Canadian Journal of Soil Science*. 86:203-217.
- Barbour, S. L., D. Chapman, C. Qualizza, S. Kessler, C. Boese, R. Shurniak, G. Meiers, M. O’Kane, J. Hendry and S. Wall, 2004. Tracking the evolution of reclaimed landscapes through the use of instrumented watersheds – a brief history of the Syncrude Southwest 30 overburden reclamation research program. In: *International Instrumented Watershed Symposium* (Edmonton, Canada, 22–25 June), 2004. <http://www.rr.ualberta.ca/oilsands/IIWS.htm>.
- Berger, K., S. Melchior and G. Michlich, 1996. Suitability of Hydrologic Evaluation of Landfill Performance (HELP) model of the US Environmental Protection Agency for the simulation of the water balance of landfill cover systems. *Environmental Geology*, 28(4):181-189.
- Berger, K., 2000. Validation of the Hydrologic Evaluation of Landfill Performance (HELP) model for simulating the water balance of cover systems. *Environmental Geology*, 39 (11):1261-1274.
- Beven, K.J., 2001. Rainfall-runoff modelling, the primer. *John Wiley & Sons, Chichester*, 360 pp, 2001.

- Boese, K., 2003. The design and installation of a field instrumentation program for the evaluation of soil–atmosphere water fluxes in a vegetated cover over saline/sodic shale overburden. *MSc Thesis*, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.
- Carey, S.K., 2008. Growing season energy and water exchange from an oil sands overburden reclamation soil cover, Fort McMurray, Alberta, Canada. *Hydrological Processes*, 22:2847-2857.
- Cuenca, R. H., D.E. Stangel and S.F. Kelly, 1997. Soil water balance in a boreal forest. *Journal of Geophysical Research*, 102(D24):29,355-29,365.
- Dawson, C. W., R.J. Abrahart and I.M. See, 2007. HydroTest: a web-based toolbox of evaluation metrics for the standardized assessment of hydrological forecasts. *Environmental Modelling & Software*, 22:1034-1052.
- Dingman, S. L., 2002. Physical Hydrology, Second Edition. Prentice Hall, Upper Saddle River, New Jersey. 646 pp.
- Eichinger, W.E., J. Nichols, J.H. Prueger, L.E. Hipps, C.M.U. Neale, D.I. Cooper and A.S. Bawazir, 2003. Lake evaporation estimation in arid environments. *Final Report, IIHR - Hydroscience & Engineering*. The University of Iowa, Iowa City IA 52242-1585.
- Elshorbagy A., A. Jutla and J. Kells, 2007. Simulation of the hydrological processes on reconstructed watersheds using system dynamics. *Hydrological Sciences Journal*. 52(3):538–561.

- Elshorbagy, A., and L. Barbour, 2007. A probabilistic approach for design and hydrologic performance assessment of reconstructed watersheds. *Journal of Geotechnical & Geoenvironmental Engineering*, ASCE, 133(9):1110-1118.
- Elshorbagy, A., A. Julta, L. Barbour and J. Kells, 2005. System dynamics approach to assess the sustainability of reclamation of distributed watersheds. *Canadian Journal of Civil Engineering*, 32:144-158.
- Falkenmark, M., 1997. Society's interaction with the water cycle: a conceptual framework for a more holistic approach. *Hydrological Sciences*, 42:451–466.
- Ford, A., 1999. Modeling the environment: an introduction to system dynamics modeling of environmental systems, Island Press, Washington, DC, USA. 401 pp.
- Forrester, J.W., 1980a. Information sources for modeling the national economy, *Journal of American Statistical Association*, 75:555–566.
- Forrester, J.W., 1980b. System dynamics—future opportunities, *TIMS studies in the Management Sciences*, 14:7–21.
- Gee, G., and D. Hillel, 1988. Groundwater recharge in arid regions: review and critique of estimation methods. *Hydrological Processes*, 2:255.
- Geoanalysis 2000 Ltd. (2000): SOILCOVER User's manual, May 2000.
- Haigh, M.J., 2000. The aims of land reclamation, *Land Reconstruction and Management*, A.A. Balkema Publishers, Rotterdam, The Netherlands, 1:1-20.
- High Performance Systems Inc (HPS), 2001. Tutorial and technical documentation: STELLA® II, High Performance Systems Inc., Hanover, N.H. [now ISES Systems, Lebanon, N.H.].

- Iwata, Y., M. Hayashi and T. Hirota, 2008. Comparison of snowmelt infiltration under different soil-freezing conditions influenced by snow cover. *Vadose Zone Journal*, 7:79-86.
- Julta, A.S., 2006. Hydrologic modeling of reconstructed watersheds using a system dynamics approach. *M.Sc. Thesis*, University of Saskatchewan, Canada.
- Kilmartin, M.P., 2000. Hydrological management of reclaimed opencast coal mine sites, Land reconstruction and Management, A.A. Balkema Publishers, Rotterdam, The Netherlands, 1:137-158.
- Li, L., and S.P. Simonovic, 2002. System dynamics model for predicting floods from snowmelt in North American prairie watersheds. *Hydrological Processes*, 16:2645–2666.
- Mahmood, R., and K.G. Hubbard, 2003. Simulating sensitivity of soil moisture and evapotranspiration under heterogeneous soils and land uses. *Journal of Hydrology*, 280:72-90.
- Mapfumo, E., D.S. Chanasyk and C.L.A. Chaikowsky, 2006. Simulation of soil water content on a small reclaimed watershed in northern Alberta using the Root Zone Water Quality Model (RZWQM). *Canadian Journal of Soil Science*, 86:675–690.
- Mays, L.W., 2005. Water resources engineering. John Wiley & Sons, New York, USA.
- McKenna, G.T., 2002. Sustainable mine reclamation and landscape engineering. *Ph.D. Thesis*, University of Alberta, Edmonton, Alberta, Canada.
- Milczarek, M., D. Hammermeister and J. Vinson, 2000. Myths, models and realities: performance of mine reclamation cover systems in controlling infiltration and

seepage in the southwestern United States. *Fifth International Conference on Acid Rock Drainage* (Society for Mining, Metallurgy and Exploration: Littleton).

Milczarek, M., T. Yao, J. Vinson, J. Word, S. Kiessling, B. Musser and R. Mohr, 2003.

Performance of mono-layer evapotranspirative covers in response to high precipitation and extended drought periods in the South Western United States. *Sixth International Conference on Acid Rock Drainage* (Society for Mining, Metallurgy and Exploration: Littleton).

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, J.R. Williams and K.W. King, 2002. Soil and water assessment tool theoretical documentation version 2000, Texas Water Resources Institute, College Station, TWRI Report TR-191, Texas.

Parasuraman, K., A. Elshorbagy and S.K. Carey, 2007. Modelling the dynamics of the evapotranspiration process using genetic programming. *Hydrological Sciences Journal*, 52(3):563-578.

Pitman, J.I., 1989. Rainfall interception by bracken in open habitats — relations between leaf area, canopy storage and drainage rate. *Journal of Hydrology*, 105:317–334.

Porporato, A. and I. Rodriguez-Iturbe, 2002. Ecohydrology - A challenging multidisciplinary research perspective. *Hydrological Science Journal*, 47:811–822.

Porporato, A., F. Laio, L. Ridolfi and I. Rodriguez-Iturbe, 2001. Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress - III. Vegetation water stress, *Adv. Water Resources*, 24:725–744.

Quevedo, D.I., and F. FrancésFranc'es, 2008. A conceptual dynamic vegetation-soil model for arid and semiarid zones. *Hydrol. Earth Syst. Sci.*, 12:1175–1187.

- Rick, G., 1995. Closure considerations in environmental impact statements. *Mineral Industry International*, 1022:5-10.
- Rodriguez-Iturbe, I., A. Porporato, F. Laio and L. Ridolfi, 2001. Plants in water-controlled ecosystems: Active role in hydrologic processes and response to water stress- I. Scope and general outline. *Adv. Water Resources*, 24:695–705.
- Rodriguez-Iturbe, I., 2000. Ecohydrology: A hydrology perspective of climate-soil-vegetation dynamics. *Water Resources Research*, 36:3–9.
- Sankarasubramanian, A., 2002. Annual hydroclimatology of the United States. *Water Resources Research*, 38(6), 1083, 10.1029/2001WR000619.
- Schaake, J., 2002. Calibration of watershed models-Introduction, Duan et. al. (ed.), Water Science and application 6, *American Geophysical Union*, Washington, DC., 1-7.
- Schreoder, P.R, J.M. Morgan, T.M. Walski and A.C. Gibson, 1994. Hydrologic evaluation of landfill performance (HELP) model. Volume 1, User's guide, International Groundwater Modeling Centre, Colorado School of Mines, Colo., USA.
- Shurniak, R.E., 2003. Predictive Modeling of Moisture Movement within Soil Cover Systems for Saline/sodic overburden Piles, *M.Sc. Thesis*, University of Saskatchewan, Canada.
- Sloan, P.G. and I.D. Moore, 1984. Modeling Subsurface Stormflow on Steeply Sloping Forested Watersheds. *Water Resources Research*, 20(12):1815–1822.
- Strangeways, I., 2003. Measuring the Natural Environment. *Cambridge University Press*, Cambridge, UK.

- Valente, F., J.S. David and J.H.C. Gash, 1997. Modelling interception loss for two sparse eucalypt and pine forests in central Portugal using reformulated Ruttter and Gash analytical models. *Journal of Hydrology*, 190:141-162.
- Van Dijk, A.I.J.M. and L.A. Bruijnzeel, 2001. Modelling rainfall interception by vegetation of variable density using an adapted analytical model. Part 1: model description. *Journal of Hydrology*, 247:230-238.
- Van Genuchten, M. Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America J.*, 44:892-898.
- Voinov, A., C. Fitz, R. Boumans and R. Costanza, 2004. Modular ecosystem modeling. *Environmental Modelling and Software*, 19:285-304.
- Weeks, B. and G.W. Wilson, 2006. Prediction of evaporation from soil slopes. *Canadian Geotechnical Journal*, 43(8):815–829.
- Yalcin, F. and G.N. Demirer, 2002. Performance evaluation of landfills with the HELP (Hydrologic Evaluation of Landfill Performance) model: Izmit case study. *Environmental Geology*, 42:793-799.
- Yanful, E.K. and B.C. Aubé, 1993. Modelling moisture-retaining soil covers, Proceedings, *Joint CSCE/ASCE National Conference on Environmental Engineering*, Montréal, Quebec, July 12-14, 1:273-288.

Chapter 3 - Comparative Probabilistic Assessment of the Hydrological Performance of Reconstructed and Natural Watersheds

This chapter has been published as a research paper in the *Hydrological Processes Journal*.

Citation: Keshta, N., Elshorbagy, A., and Barbour, L. (2010). “Comparative probabilistic assessment of the hydrological performance of reconstructed and natural watersheds.” *Hydrological Processes*, DOI: 10.1002/hyp.7596.

Contribution of the PhD candidate

The idea for the research presented in this chapter naturally stemmed from earlier work (Elshorbagy and Barbour, 2007). The candidate extended the work to other sites (reconstructed and natural) and hydrological process, and drafted the manuscript. The second author provided critical review of the analysis and the manuscript. The third author offered some technical and editorial help.

Contribution of this chapter to the overall study

The goal of this study was to improve the utility of the generic system dynamics watershed (GSDW) model beyond prediction applications, and to use it as a tool for assessing the long-term performance of reconstructed watersheds. The hypothesis is that the robustness of the GSDW model along with the probabilistic framework initially

developed by Elshorbagy and Barbour (2007) could aid in understanding reconstructed systems. This hypothesis was tested by applying the GSDW model along with the available historical meteorological records to estimate long-term soil moisture patterns and annual evapotranspiration fluxes. A probabilistic framework was adopted and frequency curves of the maximum annual moisture deficit values were consequently constructed and used to assess the probability that various reconstructed and natural watersheds could provide the desired moisture demands. The resulting integrated information gained from mature natural watersheds and reconstructed systems improved our knowledge of the probable response of reconstructed watersheds via multiple simulations of “what-if” scenarios using various soil/vegetation alternatives; this consequently indicated the success of particular management actions. Studying watersheds of various soil types, layering, thicknesses, and topography could be adopted to predict the optimum sustainable reclaimed cover alternatives that are ecologically feasible and economically viable. The study showed a tendency for the reconstructed watersheds to provide less moisture for evapotranspiration than natural systems. Mature canopy was also concluded to positively influence the moisture deficit regime of the reconstructed covers, signifying a greater possibility that such covers will adapt to the vegetation.

3.1 Abstract

The oil sands industry has committed to returning the mine sites to a productive condition. The reconstructed soil covers must have sufficient available water holding capacity (AWHC) to supply enough moisture over the growing season, to promote vegetation. In order to assess the sustainability of various soil cover alternatives, a generic system dynamics watershed model entitled GSDW was used along with the available historical meteorological records to estimate the maximum soil moisture deficit and annual evapotranspiration fluxes. A probabilistic framework was adopted; consequently, frequency curves of the maximum annual moisture deficit values are constructed and used to assess the probability that various reconstructed and natural watersheds can provide the associated moisture demands. In general, the study showed a tendency for the reconstructed watershed to provide less moisture for evapotranspiration than natural systems. Watersheds of various soil types, layering, thicknesses, and topography were studied. The gained knowledge was used to predict the possible performance of a hypothetical reclamation cover. The results indicated that the hypothetical cover performed in a similar manner to the thickest existing soil cover which confirmed a high probability that the cover would survive under the same existing climatic conditions. Moreover, this probabilistic framework was found to be useful for integrating information gained from natural watersheds (e.g. the canopy of mature natural systems, and transfer the results to the reconstructed system). The results show that the canopy influenced the moisture deficit regime positively which signifies a greater possibility that reconstructed covers will adapt to vegetation type. In brief, the adopted

approach enables better understanding of the response of reconstructed systems via multiple simulations of “what-if” scenarios using different soil/vegetation alternatives.

3.2 Introduction

Oil sands in Alberta, Canada, were discovered beneath a complex boreal forest ecosystem comprised of a unique mosaic of forest, wetlands, and lakes. Canada's boreal forest is globally significant, representing one-quarter of the world's remaining intact forests (Lee et al., 2003). In addition to the ecosystem services it provides, such as water cleansing, storing carbon and releasing oxygen, it is also home to a wide variety of wildlife. In order to gain access to the oil-bearing formations, the overburden material is removed and stockpiled and then salvaged topsoil is placed over it. The mining process results in a large disturbance of ecological functions of nature such as the hosting of aquatic ecosystems and vegetation biomes (Haigh, 2000). The United Nations Environment Program has identified Alberta's oil sands mining projects as one of 100 key global "hotspots" of environmental degradation (UNEP, 2006). A measure of the level of potential environmental impact caused by oil sands mining is illustrated by the fact that one of the largest daily producer of oil sand has disturbed 21,282 hectares of land since 1978 of which 4,668 hectares have been reclaimed over the same time period (Syncrude Canada Ltd., 2007). According to Alberta Environment, development of the oil sands presents overwhelming challenges for boreal forest conservation and reclamation (Norah et al. 2001). The restoration of disturbed watersheds is mandatory to gain government consent to commence mining activity. With the current rate of oil sands industry

expansion, there is also a need to consider the combined and cumulative impacts arising from mining activities (e.g. future climate change, and greenhouse gas emissions).

The emphasis in the very early years of land reclamation was simply on ‘tidying up’. More recently, the emphasis has shifted to returning the land to productive use. Sustainable land reclamation strategies employ engineering measures to contain and control problems caused by the disruption of natural systems. The process of re-establishing the disturbed landscape and developing sustainable soil-vegetation-water interactions to achieve land capability corresponding to the undisturbed condition is called land reclamation (Gilley et al., 1977). Selecting the texture, thickness and final landscape is vital for any reclamation scenario. The oil sands industry has adapted a method of evaluating reclamation soil prescriptions referred to as the Land Capability Classification System (LCCS) for Forest Ecosystems in the Oil Sands (Leskiw, 2004). The LCCS classifies soils into several groups of ecosites based on available water holding capacity (AWHC) to identify the soil moisture regime for a specific management scenario. The AWHC is the volume of water stored within the rooting zone as represented by the difference in water content between field capacity and wilting point. The sites under consideration in this paper were targeted for upland forest (class “d” ecosites), and accordingly have a target AWHC value of 160 mm.

More recently, oil sands creators have been considering the use of a risk based method of managing environmental risks. The key to this approach is developing a long-term plan to reduce the impact of projects by ensuring that the disturbed lands are

returned to a stable and safe condition that is capable of supporting biologically self-sustaining communities of plants and animals (Qualizza et al., 2004). The hydrological performance of these reconstructed watersheds needs to be assessed by creating a landscape that sustains an integrated mosaic of land uses. The performance is evaluated by the ability of those landscapes to store and release soil moisture to support the vegetation during the growing season (Haigh, 2000). The large scope of sustainable watershed management requires a commitment to continuous learning and improvement through the system known as adaptive management (Noss, 1993). Salwasser et al. (1993) quoted that the desired outcome of any sustainable forest (watershed) management is a balance among different conditions that are economically viable, ecologically feasible, and socially accepted.

The probability that a plant is in a healthy state is equivalent to the probability that its response, measured by the soil moisture deficit, is less than a value representing the maximum soil moisture deficit (Mukherjee and Kottegoda, 1992). The values of soil moisture deficit and actual evapotranspiration vary with soil type and soil texture (Shaw, 1994). A similar methodology for assessing the hydrological performance of the reconstructed soil covers was adopted by Elshorbagy and Barbour (2007) to assess the risk of failure of proposed reclaimed (reconstructed) sites under various climatic scenarios. Elshorbagy and Barbour (2007) used a calibrated site-specific system dynamics watershed model (SDW) (Elshorbagy et al., 2005; Julta, 2006), along with the available historical meteorological records, to estimate the maximum soil moisture deficit the soil cover can sustain during the growing season. Frequency curves for maximum

annual moisture deficit were used to assess the probability that each cover can provide the desired threshold of moisture demand. This essentially creates a risk based representation of the AWHC concept. The adopted probabilistic approach can be used to evaluate the life cycle costs of different proposed cover alternatives (thicknesses and texture). A similar analysis is quite useful in the design and formation of newly reconstructed watersheds. A similar probabilistic approach was adopted by Candela et al. (2005) to evaluate the effect of forest fires on flood frequency curves. Candela et al. (2005) adopted a methodology that was found to provide a useful framework for detecting changes in flood magnitudes in both pre- and post-fire conditions.

The aim of this paper is to build on Elshorbagy and Barbour's (2007) probabilistic approach using a generic system dynamics watershed model (GSDW), developed by Keshta et al. (2009). The specific objectives of this paper are: (i) to evaluate the current and future hydrological performance of existing reconstructed watersheds; (ii) to introduce an approach that allows for testing and optimizing the design of reconstructed soil cover alternatives based on the knowledge gained from modeling the existing reconstructed sites; and (iii) to compare the hydrological performance of reconstructed watersheds with natural watersheds, and based on this comparison, knowledge can be transferred to assess the sustainability of the restored forests on the newly reclaimed sites. In order to establish the link between reconstructed and natural watersheds, the probabilistic approach application will be implemented on two natural and five reconstructed watersheds.

3.3 Case Studies

3.3.1 Reconstructed Watersheds

An oil sands mining company operating north of Fort McMurray (57°39'N; 111°13'W), northern Alberta, Canada, has been conducting experiments on its reconstructed watersheds (alternatively called experimental covers). The first location has three experimental covers (D1, D2 and D3) of different thicknesses (0.5 m, 0.35 m, and 1.0 m) that were constructed in 1999 over the saline-sodic overburden. Each cover is comprised of a thin peat/mineral mix layer (0.15-0.20 m thick) overlying a layer of glacial till. Each cover has an area of 1 ha (approximately 200 m long and 50 m wide), with a slope of 5H:1V (Hill slope) and was initially sown with a barley nurse crop (*Hordeum jubatum*) followed by plantings of white spruce (*Picea glauca*) and aspen (*Populus tremuloides*) tree seedlings (Boese, 2003). The second location is a reconstructed cover system located on the flat top South Bison Hill (SBH). It was constructed in 2001 of 0.2 m of peat / mineral mix overlying 0.8 m of glacial till. The area of the site is approximately 2 km², and is elevated 60 m above the surrounding landscape (Hill top). The SBH vegetation is dominated by foxtail barley (*Hordeum jubatum*) and minor species including fireweed (*Epilobium angustifolium*) (Parasuraman et al., 2007). The third location is the South West Sand Storage (SWSS), which was constructed of 0.2-0.4 m of till/secondary cover material overlaying tailings sands. It is currently the largest operational tailings dam in the world at approximately 40 m high, with an area of about 23 km². The vegetation varies from horsetail (*Equisetum arvense*), fireweed (*Epilobium angustifolia*) and white and yellow clover (*Melilotus alba*, *Melilotus officinalis*). The site was also planted with tree species including hybrid poplar (*Populus*

sp. hybrid), trembling aspen (*Populus tremuloides*), white spruce (*Picea glauca*) and willow (*Salix sp.*) (Parasuraman et al., 2007).

Intensive field instrumentation was established to measure the meteorological and soil characteristics on these sites from 1999 to date. The precipitation (mm), air temperature (°C), net radiation (W/m²), soil temperature (°C) and volumetric soil moisture content measurements are available four times daily. More details on the site description and collected data are found in Boese (2003) and Barbour et al. (2004).

3.3.2 Natural Watersheds

The study areas with natural conditions are well instrumented and part of the area of the former Boreal Atmosphere Exchange Study (BOREAS), which covers a large portion of Saskatchewan and Manitoba with an area of 1000 km by 1000 km. This region includes young and old aspen, old jack pine, and old black spruce forests.

Two natural sites are considered in this study. The first is the Old Aspen site (OA) located near the south end of Prince Albert National Park, Saskatchewan (53.63°N; 106.19°W; 600.6m). The field instrumentation of the OA site has been providing continuous measurements since 1997 as part of the Boreal Ecosystem Research and Monitoring Sites (BERMS) program. The soil is well drained loam to clay loam. The top 0.1 m is an organic layer (leaf litter, plus fermentation layer) and the underlying mineral soil consists of an upper layer of 0.07-0.3 m of till mixed with sand and clay, overlying a layer of 0.45 m derived from gravely and clay enriched till. The forest canopy is

dominated by trembling aspen with an average height of 21 m and the understory canopy consists of 2 m high beaked hazelnut (*Corylus cornuta*) (Balland et al., 2006). Thermocouple sensors are used to measure soil temperature every 30-min at depths of 0.02, 0.05, 0.10, 0.20, 0.50 and 1.00 m below the moss layer. CS615 soil moisture sensors (TDR) are used to measure the volumetric moisture content of the soil at 0.08, 0.23, 0.45, and 1.05 m below the ground surface. Net radiation (NR) is measured using Middleton CNR-1 net radiometer above the canopy. Measurements of the latent heat fluxes are made with the eddy covariance technique (EC) and reported at 30 minute intervals. Leaf area index (LAI) is measured near the flux tower using a plant canopy analyzer (PCA) (model LAI-2000) and found to be $5.5 \text{ m}^2/\text{m}^2$. Additional information regarding the saturated hydraulic conductivity and the soil water retention function can be obtained from Cuenca et al. (1997).

The second site is the Old Jack Pine (OJP) watershed, located north east of Prince Albert, Saskatchewan (53.91°N; 104.69°W; Elev. 579.27 m) (BOREAS coordinates). The site is dominated by mature jack pine (*Pinus banksiana* Lamb) established in 1914 with heights from 12 to 15 m. The understory consists of sparse green alder (*Alnus crispa*) and predominantly lichens (*Cladina* spp.) ground cover. The canopy leaf area index is $1.7 \text{ m}^2 \text{ m}^{-2}$. The soil is well drained sand, 1.05 m in depth. The field instrumentation of the OJP site has been providing continuous measurements from 1998 to 2002. The soil moisture measurements are taken every four hours, at depths of 0.15, 0.30, 0.60, 0.90, 1.20 and 1.50 m below ground surface. Thermocouple sensors are set to measure the soil temperature every 30 minute, at depths of 0.02, 0.05, 0.10, 0.20, 0.50

and 1.00 m below ground surface. Meteorological measurements at both natural sites are sampled every 5 seconds, and outputs are averaged every 30 minutes, year round and are available from BOREAS/BERMS database (Balland et al., 2006). The data was aggregated in a daily scale bases for executing the GSDW model.

3.4 Hydrological Modeling

3.4.1 Model Description

The GSDW model is a mechanistic, semi-empirical, lumped watershed model capable of simulating various components of watershed hydrology, such as canopy interception, evapotranspiration, surface runoff, lateral interflow, infiltration, and soil moisture redistribution in unsaturated/saturated layers, based on the surface energy and water balances. The model requires daily meteorological data (e.g., precipitation, air temperature, relative humidity, wind speed, and net radiation), plant community data (leaf area index and canopy storage), soil properties, and rudimentary site descriptors (e.g., field capacity, porosity, saturated water content, residual moisture content, van Genuchten empirical parameters for suction calculations, gradient, texture and layer thicknesses). This model is an upgrade/generalization of a site-specific SDW model which was initially developed by Elshorbagy et al. (2005) and Julta (2006). The main drawbacks of the previous SDW model version were that it had no flexibility in choosing the number of soil layers, thickness, and topographic inclination. Also, soil water characteristic curves (SWCC) were pre-requisite for the SDW model to identify movement of soil moisture in unsaturated conditions. The modified version of the model

was adapted to select the number of soil layers, stratification, and topographic inclination of the site. A provision was made in the model for interflow and runoff components to account for the effect of topography (surface slope). The van Genuchten (1980) equation was implemented in the model to describe the SWCC. The SDW model did not consider canopy interception in spite of the importance of canopy interception losses, which can vary from 10-40% of the total precipitation, depending on plant communities (Dingman, 2002). A canopy interception module was developed and added to the GSDW model to overcome this problem.

The system dynamics (SD) simulation environment (STELLA) (HPS, 2001) was used to model the watershed as a dynamic system, based on the concept of stock-flow, in a user-friendly environment. The SD approach tolerates building a tentative knowledge of the relation between two parameters by incorporating a qualitative relationship between those parameters, as well as having the potential of implementing a combination of empirical formulations and physically based concepts (Elshorbagy et al., 2007). The model uses empirical (fitted-parameter) formulations to calculate actual evapotranspiration, van Dijk and Bruijnzeel (2001) analytical model for canopy interception, and the van Genuchten (1980) equation to account for matric suction-soil moisture relationship. Also, the conceptual model of Valente et al. (1997) was incorporated into the model as another alternative to simulate interception losses.

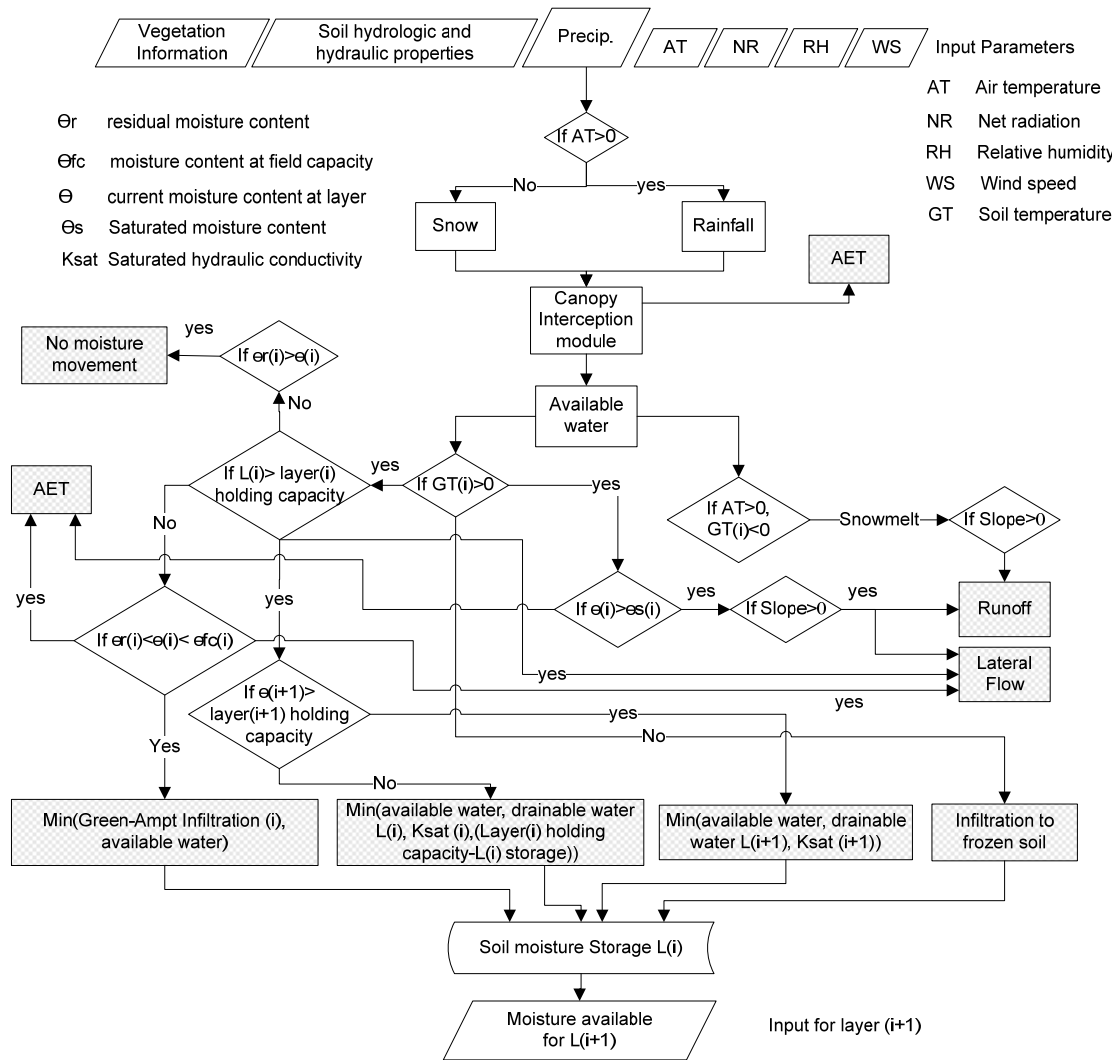


Figure 3-1 A flow chart of the procedure of which the GSDW model follows to accommodate various hydrological processes in top layer.

In addition to the previously mentioned empirical equations, a set of physically based formulations was incorporated to the model (e.g., Green-Ampt for infiltration and soil moisture redistribution; Penman equation for potential evapotranspiration). Figure 3-1 shows a flow chart of the procedures that the GSDW model follows to simulate the various hydrological processes in the top layer. The subsequent layers follow the same procedures described for the top layer subject to the constraint that no downward

moisture movement is allowed if the suction of the upper layer is greater than that of the lower layer. More details of the model formulations can be found in Keshta et al. (2009).

3.4.2 Methodology

The hydrologic performance of reconstructed watersheds is assessed based on their ability to store and release enough moisture to maintain land-atmospheric fluxes and vegetation growth. The calibrated and validated GSDW model was used to conduct long term hydrological simulations using a period of 50 years (1953-2002) of historical meteorological input data. The long term meteorological dataset included the consequences of high probabilities of dry or wet climatic conditions.

The GSDW model was manually calibrated by adjusting the model parameters and executing a series of simulations until an acceptable level of match was obtained between the observed and simulated soil moisture values and evapotranspiration fluxes. Model error measures (e.g., the mean absolute relative error (MARE), correlation coefficient (R), and root mean squared error (RMSE)) were used to check the simulation accuracy in addition to visual inspection of soil moisture patterns and evapotranspiration fluxes (Keshta et al., 2009). It was found that the model was sensitive to lambda coefficients, a main factor in the actual evapotranspiration (AET) formulation, and infiltration coefficients, which directly affect the moisture distribution in each soil layer. In the GSDW model, soil moisture movement is restricted to or from that layer once the soil temperature in this particular layer is 0°C or below. The historical set of data offered by the Environment Canada website does not include soil temperature values for the

modeled sites, whereas soil temperature measurements are needed in the GSDW model to track soil moisture movement between layers. The literature suggests that there is a high correlation between the air temperature and ground temperature for the skin layer (Zheng et al., 1993; Paul et al., 2004). In this study, a Genetic Programming (GP) model was developed as a tool for predicting the soil temperature based on a set of measured data during the extensive monitoring program for each site. Monitored values of precipitation and air temperature were used along with the GPLAB, a genetic programming toolbox for MATLAB, developed by Silva (2003) to simulate top layer soil temperature. The total number of generations was 200 with a population size of 25 members. For the subsequent layer, the same set of input data was used along with the preceding soil temperature and the GPLAB to predict soil temperature for this layer. The deduced equations from GPLAB for each layer were used to simulate the soil temperature for the long term simulation period for that layer.

The probabilistic framework proposed by Elshorbagy and Barbour (2007) was adopted to assess the probability of various reconstructed and natural watersheds to provide the desired moisture threshold over 50 years of simulations. For each soil cover, the daily volumetric moisture content of the cover layers was predicted using the validated GSDW model along with historical meteorological records. Soil moisture content values in each cover were converted to soil moisture content (mm) stored in each layer by multiplying those values by the respective thicknesses of the soil layer in each cover. The soil moisture values of all layers within the root zone of a soil cover were added to get the daily stored soil water volume within each cover (S_t). The daily

moisture deficit (D_t), which could be attributed to evapotranspiration, was then calculated as follows:

$$\Delta S = S_t - S_{t+1} \quad (3.1)$$

$$D_t = \Delta S - (I + P) \quad (3.2)$$

where ΔS is the difference in soil moisture content between the current day (S_t) and the immediate subsequent day (S_{t+1}), I is the interflow, and P is percolation below the cover depth. A positive value of D_t indicates the depletion of soil moisture due to evapotranspiration. In other words, D_t represents the amount of water that the soil cover stored and released for vegetation in time t . The daily D_t values over the growing season were accumulated, and the maximum cumulative D_t obtained in a year is called maximum annual soil moisture deficit (D_m). The D_m values reflect the performance of the sub-watershed considering the wetness and dryness of the year as well as the precipitation variability. A positive value of D_m represents the maximum amount of moisture that the soil cover stored and released in any year. A negative value indicates that there was a water surplus, which is of less importance regarding the design of the soil cover. The annual D_m values, as well as the annual AET values (50 values representing 50 years) were treated as a random variable and probability distributions were derived and fitted to both values for each soil cover with the help of @Risk Bestfit 4.5.5 software (Palisade Corporation 2005). The frequency curves were used to define a particular

probability of non exceedance for moisture stored and released for vegetation. This probabilistic assessment approach provides an insightful visualization of the hydrological sustainability of the reconstructed watershed. In order to evaluate the performance of different vegetation alternatives and soil textures on the soil moisture deficit regime, and to establish a link between reconstructed sites and natural watersheds, long term simulations were carried out on the natural watershed as well. The same, previously described, probabilistic framework was adopted to obtain D_m and AET flux frequency curves for the natural watersheds.

In general, the long term simulations were carried out to help in understanding the relationship between reconstructed and natural systems. The generated scenarios would help to address the following queries: “Could we use the knowledge gained from existing reconstructed covers to suggest an approach to optimize future reclaimed sites?”. Another query is, “What would be the hydrological effect of introducing mature canopies such as those in mature natural watersheds to the reconstructed watersheds?”. Long term simulations on both the reconstructed and natural systems were carried out using the same climatic data as for the reconstructed sites. There were two reasons for this approach: (i) both reconstructed and natural watersheds are located in a semi-arid region having almost the same climate constrain, and (ii) it ensures that the comparative hydrological performance analysis of reconstructed watersheds and natural watersheds are based on a common climatic basis. Owing to the uncertainty in the estimation of maximum moisture deficit from input data, model structure, model parameters and

formulations, a margin of safety should be taken into consideration while relying on this probabilistic approach for designing the soil covers.

3.5 Results and Discussions

3.5.1 Hydrological Performance Assessment for Reconstructed Inclined Watersheds

The maximum annual soil moisture deficit, D_m , was obtained and treated as a random variable to fit the cumulative probability distribution curve. More than 15 distributions were tested and the best fit distributions were selected for each cover using Chi-squared goodness of fit test. The best distributions were found to be Logistic (α , β) for the D1 cover, Normal (μ , σ) for D2 cover, and InvGauss (μ , λ) for the D3 cover. In the Logistic distribution, α and β are the continuous location and shape parameters. In the Normal distribution, μ , and σ are mean and standard deviation. The parameters in the InvGauss, inverse Gaussian (or Wald) distribution are mean (μ) and shape parameter (λ) (Palisade Corporation, 2005). The fitted distributions are presented in Figure 3-2 (a, b, and c) for the covers D1, D2, and D3, respectively.

The details of the D_m distributions for the D1, D2, and D3 covers are as follows:

Soil cover D1 (50 cm); Logistic(52.1, 10.9)

Soil cover D2 (35 cm); Normal(42.3, 15.8)

Soil cover D3 (100 cm); InvGauss(351.1, 23998.6) Shift=-271.6

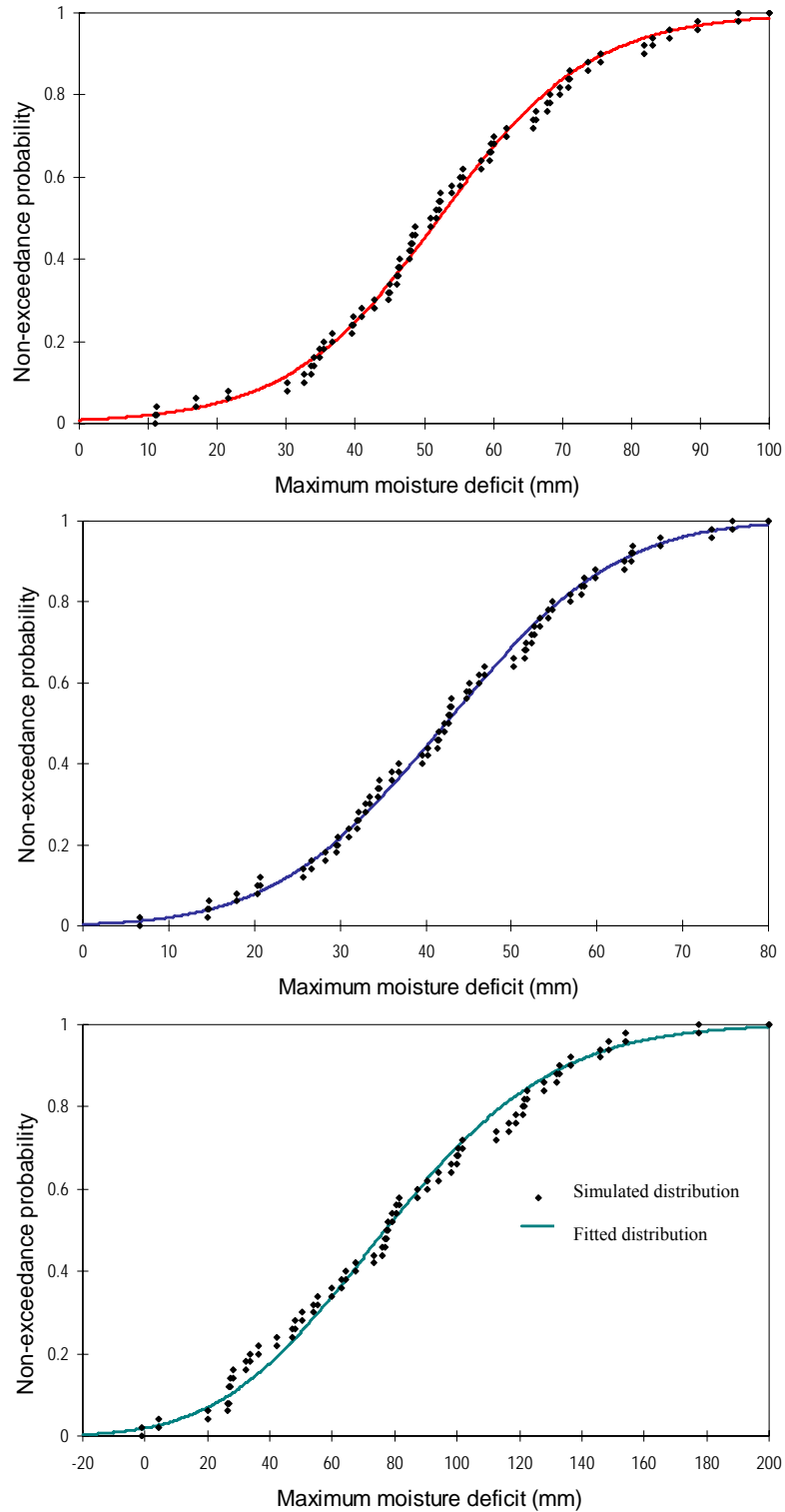


Figure 3-2 Frequency curve of maximum moisture deficit of soil covers a) D1 cover, b) D2 cover, and c) D3 cover.

The negative values of D_m indicate a water surplus where positive values indicate the ability of the soil cover to store-and-release moisture for vegetation. In the D3 cover, there are a few instances where the cover has negative values of D_m , suggesting that water may consequently exit in the form of either interflow, or deep percolation. The positive values of D_m contribute to the water requirements such as vegetation requirements and evaporation needs. The cover D1 is capable of storing and releasing up to 100 mm of moisture if certain climatic conditions mandate (99 % non-exceedance probability). At the same time, the covers D2 and D3 have D_m values of 79 mm and 189 mm, respectively, at 99% non-exceedance probabilities. Hence, when the covers are under the stress of high water requirements, the D3 cover might be able to release the moisture needed while covers D1 and D2 may fail to release adequate moisture. The D3 cover able to store and release up to 135 mm of moisture at a non-exceedance probability of 90%, indicating that this thickest cover may only be required to store-and-release this amount of moisture ten times in 100 years.

To evaluate the performance of the GSDW model and its utility for the design of future soil covers, a hypothetical cover (Dhyp) was used which consisted of 20 cm of peat mineral mix layer overlying 50 cm of glacial till. Estimating the Dhyp model parameters was a challenging task as there were no observed data to calibrate the model. To overcome this problem, a descriptive analysis for the existing D-cover model parameters was conducted. The results showed a concurrence in selecting model parameters and cover thickness, which affects the store and release abilities of each cover, particular as it affects AET and infiltration-related parameters. Based on this

analysis, the soil properties of Dhyp were considered similar to the existing D-covers. Consequently, the calibration parameters were selected as averages of the D1 and D3 calibration parameters. Figure 3-3 shows the probabilistic hydrological performance of D1, D2, D3 and Dhyp watersheds relative to each others. The details of the D_m distribution for the hypothetical cover were found to be BetaGeneral (α_1 , α_2 , min, max). The D_m frequency curve indicates that the maximum ability of this cover to store and release moisture for vegetation is around 150 mm and 110mm at 99% and 90% non-exceedance probabilities, respectively. The D3 curve is situated to the right of the Dhyp indicating its higher ability to store and release water as compared to the Dhyp cover.

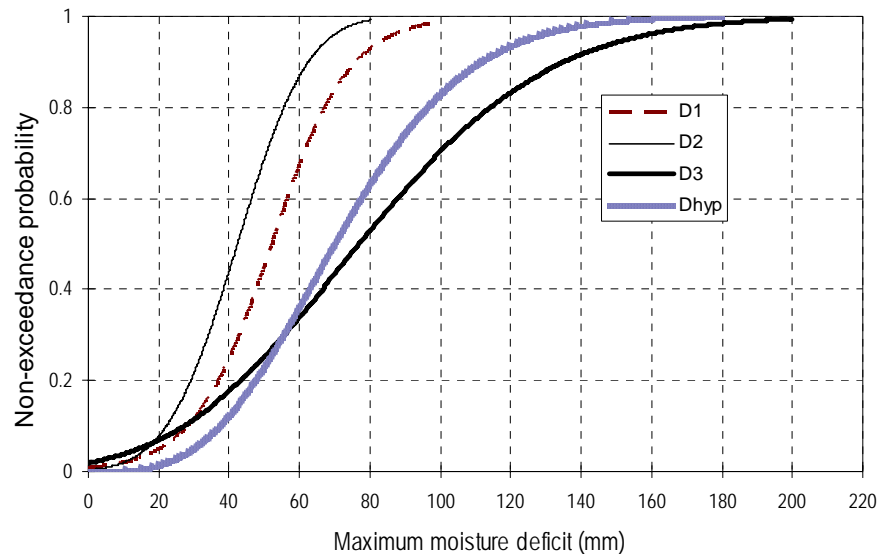


Figure 3-3 Stochastic comparison between the hydrological performances of the D1, D2, D3, and Dhyp sub-watersheds.

As mentioned in the introduction, the ultimate goal for any sustainable watershed management alternative is a balance between being ecologically feasible and

economically viable. The Dhyp cover soil moisture deficit regime showed that it has a comparable hydrologic performance as the D3 cover, which suggests that this hypothetical cover could survive under the same climatic conditions as the existing D3 cover. Conversely, the Dhyp cover is 30 cm thinner than the D3 cover and consequently would substantially reduce reclamation costs.

3.5.2 Hydrological Performance Assessment of Reconstructed and Natural Horizontal Watersheds

The best fit probability distribution of the D_m values for the SBH (Hill top) was found to be a Weibull (α , β), where α is the shape parameter and β is scale parameter. Figure 3-4 shows that the SBH soil cover is capable of storing and releasing around 117 mm of moisture under the 99 % non-exceedance probability, and 88 mm at a non-exceedance probability of 90%. For the Natural OA site, the best distribution to fit the D_m values was found to be Weibull (α , β), as well. The OA site is capable of releasing around 182 mm of moisture at 99 % non-exceedance probability, and 130 mm at a non-exceedance probability of 90%. Figure 3-4 shows the D_m frequency curves of both SBH and OA (horizontal) sites. The reconstructed SBH cover appears to have a lower store and release ability than the OA site. The OA site was able to store and release 130 mm about 10% of the time for the same climatic conditions. This observation should be treated with caution for several reasons: first, because of the uncertainties associated with the model; and second because the canopy distribution can alter the land-atmosphere interaction by keeping the subsoil moisture trapped under the canopy for longer period

(Entekhabi et al., 1996), and third, the reconstructed SBH could still be evolving toward more mature conditions.

The reconstructed SWSS and the natural OJP watersheds were treated as comparable since both of the sites have comparable soil textures being mostly comprised of sand. The best fit probability distribution of the D_m values for both sites was found to be a Normal (μ , σ), which is consistent with our initial assumption that they are comparable. Figure 3-4 shows that the OJP seems able to store and release around 190 mm of water at a 99 % non-exceedance probability, whereas the SWSS site, was only able to store and release 160 mm of water under the same meteorological conditions. This higher ability to store and release moisture in both the OJP and SWSS sites is attributed mainly to the soil texture associated with the well drained sandy soil.

It is noteworthy that though both SBH (Hill top) and the D3 cover (Hill slope), are similar in texture, thickness, and soil stratification; the SBH site has a tendency to store and release less moisture than the D3 cover. This finding could be attributed to the topographic inclination of the D3 cover. This inclination affects the soil moisture movement rates within the soil layer. It was also observed by field personnel that the SBH is poorly drained with free water sometimes trapped in the soil profile. The details of the D_m distributions for the OA, SBH, OJP, and SWSS sites with their existing vegetation are as follows:

SWSS site; Normal(61.2, 43.2)

SBH site; Weibull(2.7, 70.1) Shift=-7.7

OA site; Weibull(2.2080, 96.325) Shift=-10.373

OJP site; Normal(71.7, 51.1)

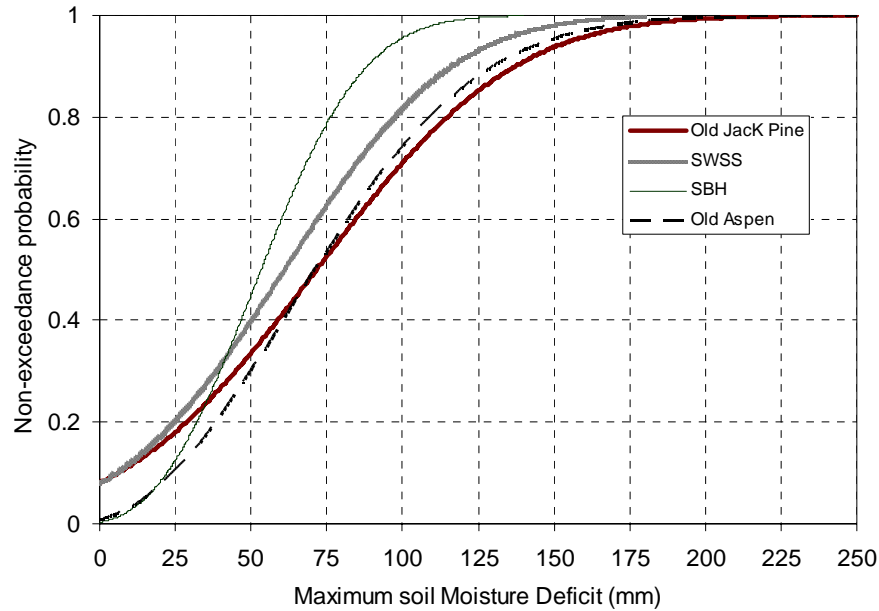


Figure 3-4 Stochastic comparison between the hydrologic performances of the OA, SBH, OJP, and SWSS sites.

3.5.3 Hydrological Performance Assessment of Vegetation Alternatives

The GSDW model was also used to establish a relation between the performance of the existing reclaimed sites and natural sites with regard to their ability to hold and release soil moisture for different vegetation alternatives. To assess the comparative hydrological performance of those covers under the same climate and vegetation, two simulation scenarios were generated for the reconstructed SBH watershed. In the first scenario, the mature vegetation of the natural OA site was brought on to the reconstructed system (SBH site) by replacing the vegetation model parameters of the reconstructed system with the parameters of the natural system (e.g. LAI, maximum leaf storage). The

same procedure was repeated by bringing the OJP watershed vegetation parameters to the reconstructed system.

The long term scenarios and consequent D_m frequency curves give an initial idea of the ability of the reconstructed watershed to supporting different mature vegetation, in terms of its long term hydrological response. Figure 3-5 shows the D_m frequency curves of both SBH, OJP and OA sites along with the two generated scenarios of the reconstructed system with the natural system vegetation alternatives.

The SBH soil cover was capable of releasing around 117 mm of moisture at 99% non-exceedance probability, and 88 mm occurs at a non-exceedance probability of 90% with its existing immature vegetation. By introducing the OA canopy to the reconstructed site, the reconstructed system showed a D_m value of about 150 mm at 99% non-exceedance probability and 110 mm at 90% non-exceedance probability with a value of LAI $5.5 \text{ m}^2/\text{m}^2$. Whereas, the SBH site was capable of releasing 134 mm at 99% non-exceedance probability and 96 mm at 90% non-exceedance probability with the OJP canopy parameters with a LAI-value of $1.7 \text{ m}^2/\text{m}^2$. The previous D_m values indicated that the model performance was correlated to the vegetation parameters of the natural systems. The evolution of the ability of the reconstructed SBH watershed to store and release water was enhanced using mature vegetation. This supports the idea that this site might modify its storing/releasing abilities with the development of vegetation over time. The D_m values for the SBH site with the existing canopy and the SBH along with the

natural system's canopy were statistically tested. As the three sets of D_m values have different distributions, a non parametric test was conducted on a multiple related sample using Kendall's test for the analysis. The analysis showed a Kendall's coefficient of concordance of 0.212, a Chi-squared value of 21.16 with two degrees of freedom, and a p-value of zero at 95% confidence level. This shows a significant difference in the means and the variance of the three D_m sets, which reflects statistically significant differences in their moisture storing and releasing abilities. The D_m distributions were fitted to demonstrate the effect of using different vegetation alternatives for the reconstructed SBH site. The details of the distributions are presented as follows:

SBH site with OJP site canopy; Logistic(58.0, 17.2)

SBH site with OA site canopy; Weibull(2.4, 90.1) Shift=-17.8

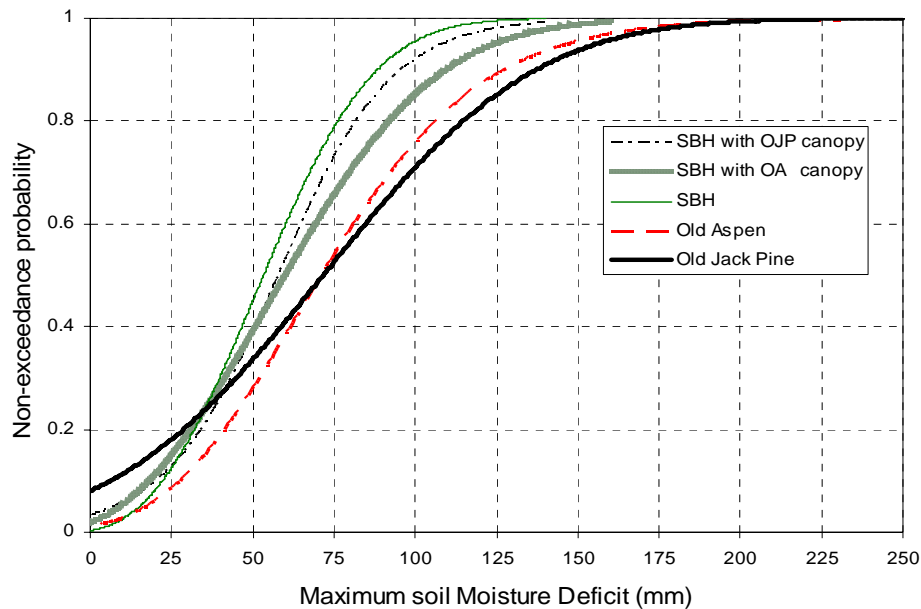


Figure 3-5 Stochastic comparison between the hydrological performances of the SBH site using different vegetation alternatives.

3.5.4 Hydrological Performance Assessment of Actual Evapotranspiration (AET) Fluxes for Different Sites

Infiltration, soil moisture redistribution and actual evapotranspiration (AET) are the main hydrological processes affecting the behavior of natural and reconstructed watersheds in arid and semi-arid regions where runoff is limited. Hydrological processes, such as soil moisture redistribution and AET, are intrinsically linked; therefore, the understanding of their mutual interaction could lead to more accurate simulations of the water balance. In fact, vegetation dynamics are controlled by climate and soil moisture, whereas vegetation in turn modulates the total water balance (Arora, 2002). Vegetation acts as the transitional link between soil and the atmosphere via the evapotranspiration process. As well, it affects the soil hydraulic and mechanical properties and surface energy budget (soil temperature) (Falkenmark, 1997).

The effect of vegetation was shown in the previous section on the soil moisture regime of the reconstructed SBH site. In this section, the actual evapotranspiration (AET) fluxes distribution was constructed to identify the ability of each watershed to release water for evapotranspiration. The simulated daily AET values were summed for each growing season and the total annual values were treated as a random variable out of the 50 years of simulation, and used to fit probability distribution curves of AET fluxes.

Figure 3-6 shows the fitted distributions of the annual growing season AET fluxes. At 90% non-exceedance probability, transpiration at the natural watersheds (both the OJP and OA sites) was 360 mm and 410 mm, respectively. For the reconstructed

watersheds (SBH and SWSS) about 323 mm and 330 mm of moisture, respectively, was released under the same meteorological conditions. More importantly, under extreme conditions (e.g., 99 % non-exceedance probability), the natural system may allow for as much as 410 mm and 500 mm of evapotranspiration for the OJP and the OA, respectively. The reconstructed sites provided around 360 mm of evaporative flux for both sites. The reason for this difference is attributed to the fact that the reconstructed system's vegetation is still immature, whereas the vegetation for the natural watersheds is mature. Also, the soil properties of the natural watershed are stable, while the reconstructed watersheds are likely still evolving in terms of their hydrologic behavior and properties. The details of the AET probability distributions are presented below:

SBH site; Normal(271.7, 39.9)

OA site; Weibull(1.5416, 122.56) Shift=+200.10

SWSS site; Weibull(2.4, 97.7) Shift=+192.8

OJP site; Logistic(314.7, 21.1)

The OJP watershed was capable of storing and releasing more soil moisture than the OA watershed under high stress demands. This is only valid for the watersheds under consideration, keeping in mind that soil texture of both sites are different and this may alter the moisture regimes. Moreover, Balland et al. (2006) mentioned that the OJP watershed canopy coverage provides a thermal insulation to the soil during summer, which allows for better moisture storing abilities (by reducing the amount evaporation fluxes from the soil cover). To evaluate the effect of vegetation individually, the SBH long term simulation was

revisited using the vegetation of the natural watershed. The moisture regimes showed a response to the vegetation canopy of both natural systems with different frequencies under the same meteorological conditions. This difference in response was attributed to vegetation related parameters (e.g. LAI, and leaf storage capacity). In general, the study showed that all the reconstructed watersheds had less store-and-release abilities, and allow for less evapotranspiration fluxes than the natural watersheds. In addition, the analysis shows that the reconstructed watersheds were able to respond positively by providing more moisture for the mature vegetation. This could reflect a reasonable success of the design of the current reconstructed watersheds.

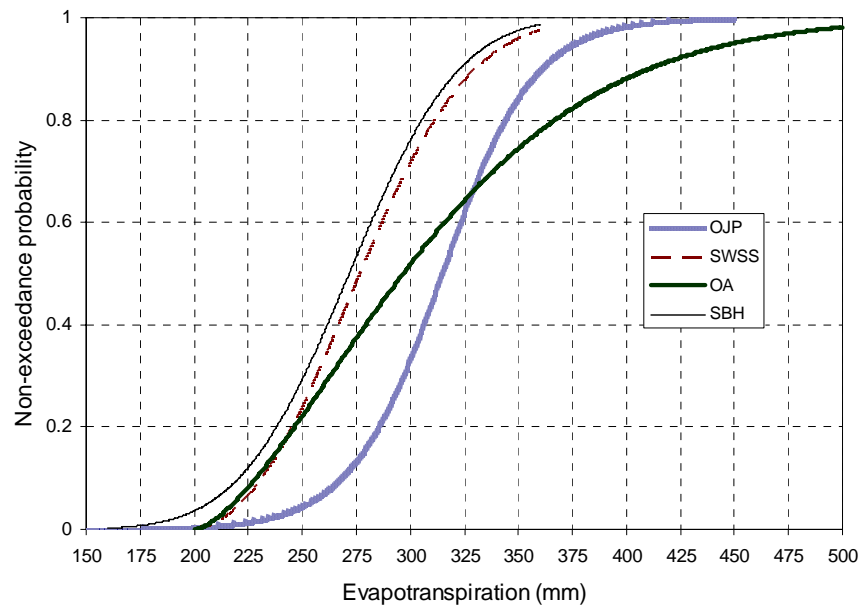


Figure 3-6 Frequency curve of growing season evapotranspiration fluxes.

3.6 Conclusions

The concept of the hydrological failure of reconstructed watersheds is redefined here because the performance of the watershed is subject to a number of hydrological and physical factors that cannot justifiably be modeled as a deterministic function. These factors arise mainly from the following: precipitation, evapotranspiration, and soil texture. Due to the numerous factors that are involved in reconstructed sites during the growing season, it is almost impossible to account for the influence of each factor individually. Therefore, the technique of using the maximum soil moisture deficit is used to generalize the combined effect of all factors. In this study, an attempt was made to assess the hydrological performance of three reconstructed soil covers (35 cm, 50 cm, and 100 cm thick) based on their soil moisture holding capacity using a system dynamics approach. Using long term climatic data, the hydrological performance of the reconstructed covers was assessed with the help of a probabilistic approach. The results indicate that the thickest soil cover is able to release more moisture under high water demands, while the other two covers may fail to release the same amount of moisture under high stress levels. The proposed hypothetical alternative (Dhyp) with intermediate thickness seems to release similar amounts of moisture as the D3 cover. It was capable of releasing 150 mm at 99% non-exceedance probability compared to 190 mm for the D3 cover. The Dhyp cover soil moisture regime is close to that of the thickest (D3) cover, which gives an indication that this hypothetical cover could survive under the same climatic conditions as the existing D3 cover. Adopting this hypothetical cover for future design purpose, or even adopting the same probabilistic technique to suggest other cover

alternatives, could enhance our knowledge in choosing the optimum sustainable reclaimed cover which is ecologically feasible and economically viable.

In general, the model also showed that the natural systems are storing/releasing moisture, especially under extreme conditions, better than the reconstructed systems. It is noteworthy that the SBH cover responded positively by the introduction of the canopy of a mature natural system, suggesting that there is a possibility for the reconstructed covers to adapt to vegetation type. Once the level of protection to be provided by the margin of safety is specified by decision makers, this probabilistic approach could be applied to verify the success of a particular management action, e.g., the use of certain vegetation type, texture, and landscape topography (flat or inclined). Obviously, the more information that is gained from natural and reconstructed watersheds, with different vegetation, textures, stratifications, and thicknesses, the less uncertain the results will be. It is also recommended that the simulated sites be revisited in future to revalidate the findings of this study.

3.7 Acknowledgements

The authors acknowledge the financial support of the Natural Science and Engineering Research Council (NSERC) of Canada, Cumulative Environmental Management Association (CEMA), the Egyptian government scholarship program, and the Department of Civil and Geological Engineering, University of Saskatchewan, Canada.

3.8 References

- Arora, V., 2002. Modeling vegetation as a dynamic component in soil-vegetation-atmosphere transfer scheme and hydrological models. *Reviews of Geophysics*, 40:1006, doi:10.1029/2001RG000103.
- Balland, V., J. Bhatti, R. Errington, M. Castonguay and P.A. ARP, 2006. Modeling snowpack and soil temperature and moisture conditions in a jack pine, black spruce and aspen forest stand in central Saskatchewan (BOREAS SSA). *Canadian Journal of Soil Science*, 86:203-217.
- Barbour, S.L., D. Chapman, C. Qualizza, S. Kessler, C. Boese, R. Shurniak, G. Meiers, M. O’Kane, J. Hendry and S. Wall, 2004. Tracking the evolution of reclaimed landscapes through the use of instrumented watersheds—A brief history of the Syncrude Southwest 30 Overburden Reclamation Research Program. *Proc., Int. Instrumented Watershed Symp.*, Edmonton, Canada, (www.rr.ualberta.ca/oilsands/IIWS.htm).
- Boese, K., 2003. The design and installation of a field instrumentation program for the evaluation of soil-atmosphere water fluxes in a vegetated cover over saline/sodic shale overburden. *M.Sc. Thesis*, University of Saskatchewan, Saskatoon, SK, Canada.
- Candela A., G. Aronica, and M. Santoro, 2005. Effects of forest fires on flood frequency curves in a Mediterranean catchment. *Hydrological Sciences*, 50(2):193–206.
- Cuenca, R.H., D.E. Stangel and S.F. Kelly, 1997. Soil water balance in a boreal forest. *Journal of Geophysical Research*, 102(D24), 29:355-365.

- Dingman, S.L., 2002. Physical Hydrology, 2nd edition, Prentice Hall, Upper Saddle River, New Jersey, pp. 646.
- Elshorbagy, A., and S.L. Barbour, 2007. A probabilistic approach for design and hydrologic performance assessment of reconstructed watersheds. *Journal of Geotechnical & Geoenvironmental Engineering*. ASCE, 133(9):1110-1118.
- Elshorbagy, A., A. Jutla, L. Barbour, and J. Kells, 2005. System dynamics approach to assess the sustainability of reclamation of disturbed watersheds. *Canadian Journal of Civil Engineering*, 32:144-158.
- Entekhabi, D., I. Rodriguez-Iturbe and F. Castelli, 1996. Mutual interaction of soil moisture state and atmospheric processes. *Journal of Hydrology*, 184:3-17.
- Falkenmark, M., 1997. Society's interaction with the water cycle: a conceptual framework for a more holistic approach. *Hydrological Sciences*, 42:451-466.
- Gilley, J.E., G.W. Gee, A. Bauer, W.O. Willis and R.A. Young, 1977. Runoff and erosion characteristics of surface mined sites in western North Dakota. *Transactions of American Society of Agricultural Engineers*, 20(4):697-704.
- Haigh, M.J., 2000. The aims of land reclamation. Land Reconstruction and Management. A.A. Balkema Publishers, Rotterdam, The Netherlands, 1:1-20.
- High Performance Systems Inc (HPS), 2001. Tutorial and technical documentation: STELLA® II, High Performance Systems Inc., Hanover, N. H. (now ISES Systems, Lebanon, N. H.).
- Jutla, A., 2006. Hydrological modeling of reconstructed watersheds using the system dynamics approach. *M.Sc. Thesis*, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

- Keshta, N., A. Elshorbagy and S. Carey, 2009. A generic system dynamics model for simulating and evaluating the hydrological performance of reconstructed watersheds. *Hydrology and Earth System Sciences*, 13(6):865–881.
- Leskiw, L.A., 2004. Land capability classification for forest ecosystems in the oil sands, Paragon Soil and Environmental Consulting Inc., Alta., Canada.
- Lee, P., D. Aksenov, L. Laestadius, R. Nogueron and W. Smith, 2003. Canada's Large Intact Forest Landscapes. *Global Forest Watch Canada*, Edmonton, Alberta. 84 pp.
- Mukherjee, D., and N.T. Kottegoda, 1992. Stochastic model for soil moisture deficit in irrigated lands. *Journal of Irrigation and Drainage Engineering*, 118(4):527-542.
- Noss, R.F., 1993. Sustainable forestry or sustainable forest?. In *Defining Sustainable Forestry*. Edited by G. Aplet, N. Johnson, J. Olson, and A. Sample. Island Press, Covelo, Calif.
- Norah, M., C. Fluet, D. Davidson, N. Krogman and M. Ross, 2001. Integrated Resource Management in Alberta's Boreal Forest: Opportunities and Constraints. <http://www.ualberta.ca/sfm>. ISBN 1-55261-132-9.
- Palisade Corporation Inc., 2005. Guide to Using @RISK. Advanced risk analysis for spreadsheets. Palisade Corporation, NY, U.S.A.
- Parasuraman, K., A. Elshorbagy and S.K. Carey, 2007. Modelling the dynamics of the evapotranspiration process using genetic programming, *Hydrological Sciences Journal*, 52(3):563-578.

- Paul, K.I., P.J. Polglase, P.J. Smethurst, A.M. O'Connell, C.J. Carlyle, P.K. Khanna, 2004. Soil temperature under forests: A simple model for predicting soil temperature under a range of forest types. *Agric. For. Meteorol.*, 121(3):167-182.
- Qualizza, C., D. Chapman, S.L. Barbour and B. Purdy, 2004. Reclamation research at Syncrude Canada's mining operation in Alberta's Athabasca oil sands region. *International Conference on Ecological Restoration SER2004*, Victoria, 24-26.
- Salwasser, H., D.W. MacCleery and T.A. Snellgrove, 1993. An ecosystem perspective on sustainable forestry and new directions for the U.S national forest system. In *Defining Sustainable Forestry*. Edited by G. Aplet, N. Johnson, J. Olson, and A. Sample. Island Press, Covelo, Calif.
- Shaw, E.M., 1994. Hydrology in practice: 3rd edition. Chapman and Hall: London, UK, pages 569.
- Silva, S., 2003. GPLAB, A genetic programming toolbox for Matlab. ITQB/UNL (<http://gplab.sourceforge.net>).
- Syncrude Canada Ltd., 2007. Online: 2007 sustainability report. (<http://www.syncrude.ca/users/folder.asp?FolderID=5909>)
- United Nations Environment Programme (UNEP), 2006. Flying around the globe on a time machine. Online: (<http://www.unep.org/Documents.Multilingual/Default.asp?DocumentID=487&ArticleID=5350&l=en>)
- van Dijk, A.I.J.M., and L.A. Bruijnzeel, 2001. Modelling rainfall interception by vegetation of variable density using an adapted analytical model. Part 1: model description. *Journal of Hydrology*, 247:230–238.

- van Genuchten, M.Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, 44:892–898.
- Valente, F., J.S. David and J.H.C. Gash, 1997. Modeling interception loss for two sparse eucalypt and pine forests in central Portugal using reformulated Ruttter and Gash analytical models. *Journal of Hydrology*, 190:141–162.
- Zheng, D., E.R. Hunt Jr and S.W. Running, 1993. A daily soil temperature model based on air temperature and precipitation for continental applications. *Climate Research* 2:183-191.

Chapter 4 - Utilizing North American Regional Reanalysis for Modeling Soil Moisture and Evapotranspiration in Reconstructed Watersheds

This chapter has been submitted as a research paper to the *Physics and Chemistry of the Earth Journal*.

Citation: Keshta, N., and Elshorbagy, A. (2010). “Utilizing North American Regional Reanalysis for modeling soil moisture and evapotranspiration in reconstructed watersheds.” *Physics and Chemistry of the Earth Journal* (Revised manuscript submitted in October 2010: JPCE-D-09-00231R1).

Contribution of the PhD candidate

Model conceptualization was performed by the candidate and the second author. The candidate carried out the computer program development and simulation, with the second author providing guidance on various aspects of the study. The text of the manuscript was drafted by the candidate, with the second author providing critical review.

Contribution of this chapter to the overall study

The previous two chapters highlight the developed generic system dynamics watershed (GSDW) model and a probabilistic framework that can be adopted to assess the performance of reconstructed watersheds compared to natural watersheds. This and the subsequent chapter identify ways to evaluate the utility of coarser data versus conventional platform data (e.g., metrological weather station data) for simulating soil

moisture and evapotranspiration. In this chapter, two versions of the GSDW model were applied: one employing the model using input data from the onsite weather station (SS-calibrated) and the other using precipitation and air temperature values from the North American Regional Reanalysis (NARR) datasets with the remaining data obtained from the onsite weather station (NARR-calibrated). These were compared based on the simulated soil moisture patterns and actual evapotranspiration. The NARR-calibrated model was shown to be reliable compared to the SS-calibrated model. The probabilistic approach implemented in Chapter 3 was also used along with the NARR long-term dataset (1979-2006) to evaluate the long-term hydrological performance of existing reconstructed watersheds with respect to soil moisture deficit. The results were compared to the findings of the previous chapter.

4.1 Abstract

Oil sands development in Canada presents overwhelming challenges for boreal forest conservation and reclamation due to the disturbance of watershed function. Modeling hydrological processes for reclaimed landscapes is essential for assessing the performance of different reclamation strategies and their evolution over time, and requires a reliable continuous source of input data. This study evaluated the utility of precipitation and temperature data from the North American Regional Reanalysis (NARR) for the hydrological modeling of two reconstructed sites located north of Fort McMurray, Alberta, Canada. NARR precipitation and air temperature data were in good agreement with the observed onsite datasets. A generic system dynamics watershed (GSDW) model was initially calibrated using the onsite meteorological data, resulting in simulated soil moisture values that slightly overestimated observed values. The model was recalibrated using the NARR temperature and precipitation data as inputs while the remaining data were obtained from the weather station. The recalibrated model was a good alternative to onsite weather station data for simulating soil moisture patterns and evapotranspiration fluxes, particularly in cases of data scarcity. The recalibrated model was used along with the NARR long term dataset (1979-2006) to evaluate the current/future hydrological performance of existing reconstructed watersheds with respect to soil moisture deficit using a probabilistic framework, and the results compared with long term performance estimates using the onsite-calibrated GSDW model. The results from both methods indicate a high probability that the reconstructed watersheds will meet the threshold of soil moisture essential for vegetation recovery. The current study demonstrates and validates the application of NARR data to hydrological modeling.

Moreover, adopting NARR data for the assessment of the long term hydrological performance of reconstructed watersheds can inform decision making with respect to the design of reconstructed soil covers.

4.2 Introduction

Canada's boreal forest, representing one-quarter of the world's remaining intact forest, is a complex ecosystem comprised of a unique mosaic of forest and wetlands that is home to wide variety of wildlife. Mining of oil sands in Alberta, Canada, results in large disturbances to the natural ecosystem as soil and overburden materials are removed and stockpiled to provide access to mined materials. The mining process is followed by land reclamation, whereby disturbed landscapes are recovered with the intent to replicate the performance of natural watersheds (Gilley et al., 1977; Haigh, 2000; Barbour et al., 2004). Alberta Environment mandates such watershed restoration prior to providing government approval for mine closure, with the main concern being whether the reconstructed watersheds will store and release enough moisture to support vegetation during the growing season. Even though hydrological processes such as infiltration, soil moisture redistribution, and evapotranspiration are the main factors affecting the hydrological response in arid and semi-arid regions, they are not widely investigated in watershed modeling literature where more attention is given to runoff simulations (Elshorbagy et al., 2007).

Many reconstructed watersheds are used for experimental research, but transferring the results of these typically small watersheds to larger scales might not be

appropriate (Gerwin et al., 2009). Most existing reconstructed watersheds are extensively monitored and the data collected is used to build a knowledge base for future reclaimed sites. However, data availability is the exception not the rule. Availability of data is a major challenge that constrains not only the type of models used but also their predictive ability and accuracy. Satellites have helped substantially with respect to overcoming such problems, but data from more conventional platforms (e.g., meteorological stations) will remain, in the foreseeable future, essential to validate satellite observations. Modeling hydrological processes requires meteorological, vegetation, and hydrological data. Unfortunately, some hydrologically important variables, such as soil moisture and evaporation-related data, are not measured on a regular basis at all sites. Some long term surface records of temperature and precipitation exist, but the number of observations is limited and the measurements are often site-specific. Thus, simulating various hydrological processes requires a reliable continuous source of input data.

Currently available global reanalyses (e.g., National Center for Environmental Prediction (NCEP), National Center for Atmospheric Research (NCAR), NCEP/DOE (Reanalysis-2), ERA-15, ERA-40) can provide reasonably accurate data. The weakest component of these reanalysis data is precipitation, which has large errors compared to ground observations, especially where topography is hummocky (Trenberth and Guillemot, 1998; Rao et al., 2002; Tolika et al., 2006). For example, when Haberlandt and Kite (1998) used NCEP/NCAR global reanalysis precipitation data to simulate streamflow in the Mackenzie River basin in north-western Canada, their results tended to overestimate streamflow due to substantial overestimates of precipitation.

The North America Regional Reanalysis (NARR) project is a reanalysis of historical observations using a 32-km version of the 180-km version NCEP reanalysis. The dataset is basically the same as used in the global reanalysis, where the 6-hourly data were converted into 3-hourly data. The objective of the NARR is to create a long term set of consistent climate data on a regional scale for the North American domain (Mesinger et al., 2003; Mesinger et al., 2006; Shafran et al., 2004). The NARR data are available on a 32 km/45-layer resolution grid over North America (United States, Canada, and Mexico) with a 3-hr time step as well as daily and monthly time steps for the period 1979 to 2006. The advantages of NARR over the NCEP/NCAR reanalysis are its higher resolution and much better treatment of land surface through the assimilation of more surface data (e.g., observed precipitation, temperature, and surface winds) and through a better representation of the terrain (e.g., heights, vegetation, soil type). The NARR dataset contains “conventional” atmospheric analyses as well as model-derived fields, which contain estimates of surface/subsurface and radiative properties (Kidwell 1995; Xie and Arkin, 1997).

Compared to the NCEP/NCAR global reanalysis, NARR shows a better correlation with in situ observations of spatial and temporal variation of precipitation (Mesinger et al., 2006; Nigam and Ruiz-Barradas, 2006; Choi et al., 2009). This better correlation is attributed to NARR’s varied sources, including the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP), a merged combination of satellite and gauge precipitation (Xie and Arkin, 1997; Shafran et al., 2004). Over Canada, the hourly precipitation analyses were obtained by disaggregating a 24-hr data

derived only from a 1° rain gauge using the Cressman successive-scan technique (Mesinger *et al.*, 2006). Woo and Thorne (2006) used a hydrological model to compare precipitation and temperature data from global reanalysis and from NARR, and their results indicated a tendency for the global reanalysis data to delay snowmelt peaks. Amenu and Kumar (2008) developed a model to investigate the effect of hydraulic redistribution by deep roots on the terrestrial climatology in Sierra Nevada eco-region using NARR data. Their results show soil moisture simulation captures the general trend but not the values, a result they attribute to the difference between simulated values (representing the average of a $0.5 \times 0.5^\circ$ grid) and the observations (point values). Recently, Choi et al. (2009) used SLURP, a semi-distributed hydrological model with temperature and precipitation data from NARR, to simulate runoff of selected watersheds in northern Manitoba. The study showed overall average correlation coefficients of 0.98 and 0.62 between the NARR and onsite observed datasets for temperature and precipitation, respectively, and an average root mean squared error (RMSE) of 3.2°C and 3.4 mm for the same datasets; as such, the authors conclude the NARR data have good potential for use as input data for modeling hydrological processes. However, NARR data have not yet been extensively investigated in hydrological modeling, and most studies conducted using NARR data have been aimed at runoff estimations rather than simulating soil moisture and actual evapotranspiration.

Because the NARR data cover the entire North American domain, they can be applied to the hydrological assessment of remote areas located far from a weather station. Our current effort focused on more extensive use of NARR data in the context of

hydrological modeling, in particular for simulating long term soil moisture to predict performance frequency curves for reconstructed watersheds. The three objectives of this study were to: (1) compare temperature and precipitation data from NARR with meteorological input data obtained from onsite weather stations in northern Alberta, Canada; (2) test the applicability of NARR temperature and precipitation data for hydrological modeling of two reconstructed watersheds; and (3) investigate the utility of the NARR long term dataset (1979-2006) to evaluate the current/future hydrological performance of the existing reconstructed watersheds with respect to soil moisture deficit using a probabilistic framework to help build a knowledge base for future reclamation scenarios.

4.3 Methods

4.3.1 Study Areas and Onsite Data Collection

The reconstructed watershed study areas were located north of Fort McMurray (57°39'N and 111° 13'W), northern Alberta, Canada. The first site was one of three experimental inclined sub-watersheds constructed by the oil sands industry to evaluate the performance of different alternatives in terms of moisture holding capacity and sustaining vegetation. The three inclined prototype soil covers—D1, D2, and D3—were constructed in 1999 with thicknesses of 0.5 m, 0.35 m, and 1.0 m comprised of 0.2 m, 0.15 m, and 0.2 m of peat/mineral mix overlying 0.3 m, 0.2 m, and 0.8 m of glacial till, respectively, overlying saline sodic shale. Only the D3 cover (depth of 1.0 m) was considered in this study. The cover has a slope of 5H:1V with an area of 1 ha, and was

seeded with barley nurse crop (*Hordeum jubatum*) as well as tree seedlings of white spruce (*Picea glauca*) and aspen (*Populus tremuloides*) (Boese, 2003). Several modeling studies have been conducted regarding the hydrological performance of the D-covers using system dynamics models, and have shed much light on the hydrological behaviour of reconstructed watersheds (Elshorbagy et al., 2005, Julta, 2006, Elshorbagy and Barbour, 2007, Keshta et al., 2009). The second study site was the South West Sand Storage (SWSS), constructed of 0.2-0.4 m of till/secondary cover material over 1.0 m of tailing sands. The vegetation at the site varies with groundcover including horsetail (*Equisetum arvense*), fireweed (*Epilobium angustifolia*), and white and yellow clover (*Melilotus alba*, *Melilotus officinalis*). Tree species include Siberian larch (*Larix siberica*), hybrid poplar (*Populus sp. hybrid*), trembling aspen (*Populus tremuloides*), white spruce (*Picea glauca*), and willow (*Salix sp.*) (Parasuraman et al., 2007). An extensive monitoring program has been carried out on both reconstructed watershed sites (since 1999 for D3; since 2001 for SWSS) to monitor their evolution. Bowen Ratio and weather stations were placed in the site to provide hourly meteorological measurements of air temperature (AT), net radiation (NR), water vapour gradients, and other meteorological variables at each of the two sites. Hydrological variables (e.g., matric soil suction, and volumetric moisture content) were measured twice a day using time-domain reflectometry (TDR) and soil suction sensors at different depths. Soil temperatures at different depths were measured on an hourly basis. Measurements of the latent heat flux were made with the eddy covariance technique (EC), and reported in 30-min intervals (Carey, 2008). More detail on the field instrumentation and monitoring program can be found in Boese (2003) and Carey (2008). For NARR data, temperature and precipitation

records from the nearest four grid points surrounding the sites were extracted and interpolated to the location of the site weather station using an inverse distance weighted linear interpolation (Shepard's Method, Shepard (1968)).

Prior to hydrological modeling, the NARR data were compared to the observed data to evaluate their suitability for hydrological modeling. The observed daily mean temperature and total precipitation were obtained from onsite stations for 2000-2006. The NARR 3-hour precipitation rates were aggregated to daily totals (mm/day); air temperature values were averaged into daily means (°C) for the same period. Precipitation values less than 0.5 mm/day have been considered zero as suggested by Reid et al. (2001) and Choi et al. (2007).

4.3.2 Model Description

The GSDW model is a lumped conceptual model designed to simulate various components of watershed hydrology (e.g., canopy interception, evapotranspiration, surface runoff, interflow, infiltration, and soil moisture redistribution in unsaturated/saturated layers) based on the surface energy and water balances in semi-arid regions. The model combines both empirical (fitted-parameter) formulations (e.g., actual evapotranspiration based on simulated soil moisture index; van Dijk and Bruijnzeel (2001) analytical model for canopy interception and van Genuchten for suction (van Genuchten, 1980)) and physically based formulations (e.g., Green-Ampt for infiltration and soil moisture redistribution (Green and Ampt, 1911); Penman equation for potential evapotranspiration (Penman, 1948)). Snowmelt was estimated using a formulation based

on the temperature index suggested by Anderson (1976) to account for the spring snowmelt. This method was used to reduce the model complexity, and to avoid the need for solar radiation data. More details of the model formulations can be found in Keshta et al. (2009). The model requires daily meteorological data (precipitation, air temperature, relative humidity, wind speed, and net radiation), vegetation information (leaf area index and canopy storage), soil properties (field capacity, porosity, saturated water content, and residual moisture content), and rudimentary site descriptors (slope, elevation, texture, and layer thicknesses). The system dynamics (SD) simulation environment (STELLA) (HPS, 2001) was used for modeling the watershed as a dynamic system based on the concept of stock-flow. In general, SD has increasingly been adopted to help avoid judgement biases as well to understand the system and its boundaries by identifying both its key building blocks and the proper representation of physical processes through relatively accurate mathematical relationships (Constanza and Ruth, 1998).

4.3.3 Hydrologic Modeling

The GSDW model was manually calibrated (Keshta et al., 2009) based on two hydrological processes connected with the ecological function of the reconstructed watersheds (e.g. soil moisture and actual evapotranspiration (AET)). Calibration was performed by setting individual parameter values and executing a series of simulations, and this trial and error procedure was implemented until no further improvement in the values of the error measures was achieved. Also, visual inspection between observed and simulated soil moisture was used as another indicator of goodness of fit for the results. The goodness-of-fit between the measured and simulated datasets were generally

quantified using multiple performance indicators, providing different aspects of comparison; the root mean squared error (RMSE), the mean absolute relative error (MARE), and the correlation coefficient (R) were used as the main performance indicators, and were defined, respectively, as:

$$\text{RMSE} = \left[\frac{1}{n} \sum_{i=1}^n (O_i - S_i)^2 \right]^{0.5} \quad (4.1)$$

$$\text{MARE} = \frac{1}{n} \sum_{i=1}^n \left| \frac{O_i - S_i}{O_i} \right| \quad (4.2)$$

$$R = \frac{\sum_{i=1}^n (O_i - \bar{O}_i)(S_i - \bar{S}_i)}{\sqrt{\sum_{i=1}^n (O_i - \bar{O}_i)^2 \sum_{i=1}^n (S_i - \bar{S}_i)^2}} \quad (4.3)$$

where n represents the number of instances presented to the model; O_i and S_i represent observed and simulated counterparts; and \bar{O}_i and \bar{S}_i represent the mean of the corresponding variable.

The GSDW model was calibrated for the year 2003, for both sites, and validated from 2004 to 2006 for the D3 cover and from 2005 to 2006 for the SWSS site. For each site, two different versions of the GSDW model were generated based on the source of weather data for calibration and validation purposes. The first model was calibrated using input data from the onsite weather station (the “SS-calibrated GSDW model”). The second model was calibrated using precipitation and air temperature values from the NARR datasets, while the remaining data were obtained from the onsite weather station

(the “NARR-calibrated GSDW model”). The output from each run was compared to observed soil moisture values in terms of RMSE, MARE, and R. The model versions were compared to evaluate the effect of inconsistency of NARR datasets and the onsite weather station data on the simulated soil moisture. The key parameters adjusted during the calibration include λ_i (dimensionless) and C_1 (mm/day⁰C), which are the main factor in the actual evapotranspiration (AET) formulation, and infiltration coefficient that directly affect the moisture distribution in each soil layer (Table 4-1). Calibration parameters of C_1 and C_2 , in both watersheds, was higher for the top layer than the subsequent layer; indicating a higher moisture contribution of the surface layer toward the evapotranspiration and vegetation water requirements than the second layer. Also, those parameters showed a tendency in NARR-calibrated models to contribute more towards the evapotranspiration compared to the SS-calibrated models.

Table 4-1 Calibration parameter values for the GSDW models

Parameter	D3		SWSS	
	SS	NARR	SS	NARR
Infiltration coefficient (Ic1) (<i>dimensionless</i>)	0.03	0.03	0.038	0.018
Infiltration coefficient (Ic2) (<i>dimensionless</i>)	0.0002	0.0002	0.002	0.002
C_1^a (mm/day ⁰ C)	0.35	0.15	1.25	1.45
C_2 (mm/day ⁰ C)	0.03	0.08	1.10	1.30
Lambda ^b (λ_1) (<i>dimensionless</i>)	3.12	3.15	2.95	4.95
Lambda (λ_2) (<i>dimensionless</i>)	0.40	0.35	1.30	0.70

(a) c_1 evapotranspiration constant (mm/day⁰C) from the (1st) layer; and (b) λ_i is an exponential coefficient, used to calculate the AET, modified from the SDW model to be temperature dependant.

4.3.4 Hydrologic Modeling

The target of reconstructed covers is to have sufficient available water holding capacity (AWHC) to supply enough moisture over the growing season, thereby promoting arability. To assess the ability of various soil cover alternatives to sustain sufficient AWHC, the NARR-calibrated GSDW model was used along with the available NARR long term meteorological data (1979-2006) to estimate the maximum soil moisture deficit. The sites under consideration were targeted for upland forest (class “d” ecosites), and have a target AWHC value of 160 mm. A probabilistic framework was adopted to obtain frequency curves of the maximum annual soil moisture deficit values to assess the probability that reconstructed watersheds could provide the desired threshold of moisture demand. Specifically, the recalibrated model was executed for 28 years of NARR meteorological data to obtain daily soil moisture values. The soil moisture values of all layers within the root zone were summed to get the daily soil moisture series of each soil cover, and the difference in soil moisture content (ΔS) between the current day (S_t) and the immediate subsequent day (S_{t+1}) computed. Accordingly, the daily moisture deficit (D_t) was computed as the difference between ΔS and the sum of the interflow and percolation below the cover, and therefore, D_t can be attributed to evapotranspiration. A positive value of D_t indicates the depletion of soil moisture (moisture deficit) due to evapotranspiration, and represents the amount of water the soil cover stored and released for vegetation in time t . Daily D_t values over the growing season were summed to obtain the maximum annual soil moisture deficit, D_m . A positive value of D_m represents the maximum amount of moisture stored and released for

vegetation in one year; a negative value indicates a year of water surplus. Elshorbagy and Barbour (2007) contains further details on the probabilistic frame work and its applications).

Treating D_m values (28 values representing 28 years of simulated D_m based on the NARR-calibrated model) as a random variable, a probability distribution was constructed. The best fit distributions were selected for each cover based on their Chi-squared goodness of fit. The frequency curves obtained from the NARR-calibrated model were compared to frequency curves from the SS-calibrated GSDW model using a 50-year dataset extracted from Environment Canada historical records.

4.4 Results and Discussion

4.4.1 Data acquisition and corrections

An accurate set of climatic data is necessary for a water balance. As a result, The TE525WS tipping bucket rain gauge and the CS705 snowfall conversion adapter were mounted on a steel stake that is located approximately 4 m from the weather station. The CS705 was placed on top of the tipping bucket with an orifice elevated at 1.1 m, surrounded by an alter wind shield to reduce the wind effect on precipitation catch. The reservoir on the CS705 was filled to the overfull mark with regular motor antifreeze and topped off with a thin layer of baby oil to prevent the antifreeze from evaporating. A catch pail was placed under the tipping bucket to retain the antifreeze as the snowfall displaces it. Each April the snowfall adapter must be removed and the tipping bucket is

replaced to its original height. In addition, snow surveys were completed to aid in calculating total precipitation. A 10 m grid was staked out over the prototype covers measuring snow depths, and snow pack densities were measured using a standard fiber glass snow corer and scale (Boese, 2003).

Typically, the eddy covariance system underestimates turbulent fluxes, sensible heat (H), and latent heat ($\lambda_v E$), resulting in a residual flux density. This underestimation is commonly attributed to high and low frequency eddies that are not measured at the sampling frequency (10 Hz) (Finnigan et al., 2003). Carey (2008) calculated the slope of the relationship between net radiation minus ground heat flux ($R_n - G$) and the total turbulent flux ($H + \lambda_v E$). The slope indicated that the eddy covariance underestimates turbulent fluxes by 17 % for all measurement periods; accordingly, H and $\lambda_v E$ values were corrected by adjusting energy balance closure (Carey, 2008).

Additional corrections to the flux measurements were done by Carey (2008): (1) fluxes were removed when the friction velocity as measured by the eddy covariance was less than 0.1 m s^{-1} or/and during periods of rainfall, and (2) flux data were removed when rapid and unexpected changes in state variables occurred over half-hour intervals using a criteria of 1.5 standard deviation from the mean value for that time period. Short half-hour breaks were filled by linear interpolation, whereas, for longer breaks, turbulent fluxes were estimated using the mean diurnal variation method by replacing missing observations by the mean for that time period based on previous and subsequent 7 day periods (Carey, 2008).

4.4.2 Evaluation of the NARR Reanalysis Data

Distributions of the percentiles for daily precipitation (mm/day) for the D3 cover (onsite station) and NARR datasets were compared (Table 4-2). The median (50th percentile) precipitation values for the evaluation period (2000-2006) at the onsite stations were zero, meaning more than 50% of the days were dry; therefore, the 75th (or higher) percentile was more meaningful in terms of comparison. The 99th percentile was higher for the station data for all years except for 2003, suggesting the reanalysis underestimates the frequency of extreme precipitation events. In general, NARR tended to overestimate the cumulative annual precipitation in a tolerable range of 60 mm or less for the D3 cover. Cumulative annual precipitation data from NARR and the onsite D3 station in 2000-2006 (Figure 4-1) indicate 2003 was the wettest year and 2004 the driest. The NARR temperature values have their distribution shifted to the right relative to the onsite station recorded temperature, suggesting a warm bias of around 2°C (data not presented). RMSE and R values between the NARR and onsite observed data were calculated for each year under consideration (Table 4-3). For precipitation, mean RMSE and R values were 2.25 mm and 0.64, respectively; corresponding values for temperature were 4.21°C and 0.96. For individual years, correlation coefficients for precipitation were much lower and more variable than those for temperature (Table 4-3); the weaker correlation could be attributed to the inconsistency of the numerical weather models in forecasting precipitation timing and location compared to onsite weather stations. In other words, an assimilated precipitation event that is modeled in NARR over the grid-box may not have actually had precipitation at the precise location of onsite weather station. NARR has been shown to overestimate cumulative annual precipitation (in some years),

likely because precipitation fell at the gauges that are assimilated into NARR was higher than the recorded in the onsite station. Moreover, Choi et al. (2009) discovered a systematic error in forecasted precipitations where large positive errors are usually followed by errors equal in magnitude and opposite in direction, and vice versa, which would in turn reduce the precipitation correlation coefficient.

Table 4-2 Percentiles of daily precipitation (mm/day) for the D3 cover (onsite station) and NARR datasets.

Year	Source	Percentile					
		5th	25th	50th	75th	95th	99th
2000	NARR	0.0	0.0	0.2	1.0	5.4	8.9
	Station	0.0	0.0	0.0	0.3	6.2	15.6
2001	NARR	0.0	0.0	0.2	1.2	5.0	7.9
	Station	0.0	0.0	0.0	0.5	6.0	18.9
2002	NARR	0.0	0.1	0.5	1.2	4.4	12.1
	Station	0.0	0.0	0.0	0.3	5.6	16.6
2003	NARR	0.0	0.0	0.2	1.2	6.9	14.9
	Station	0.0	0.0	0.0	1.0	5.9	12.8
2004	NARR	0.0	0.0	0.0	0.0	6.3	14.2
	Station	0.0	0.0	0.0	0.0	4.5	19.1
2005	NARR	0.0	0.0	0.0	0.0	7.5	14.9
	Station	0.0	0.0	0.0	0.0	6.4	19.2
2006	NARR	0.0	0.0	0.0	0.0	5.5	11.8
	Station	0.0	0.0	0.0	0.0	6.3	15.4

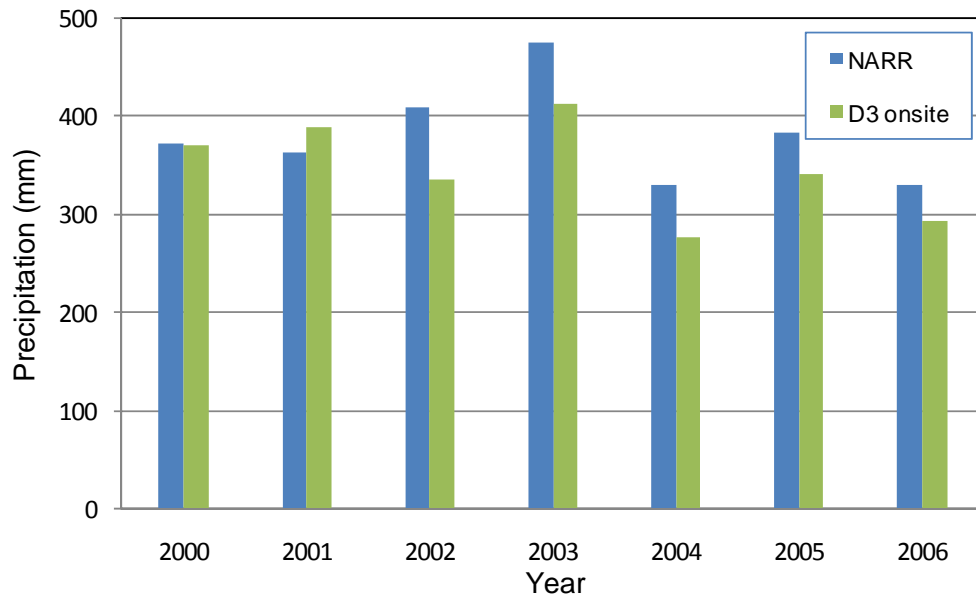


Figure 4-1. Annual precipitation from NARR and D3 onsite station data, 2000-2006.

Table 4-3 Root mean squared errors (RMSE) and correlation coefficients (R) for NARR precipitation and temperature, respectively, compared to the D3 onsite station.

		2000	2001	2002	2003	2004	2005	2006	Mean
Precipitation	R	0.69	0.58	0.76	0.50	0.55	0.75	0.65	0.64
	RMSE (mm)	2.13	2.47	1.81	2.75	2.62	2.13	2.49	2.25
Temperature	R	0.97	0.93	0.97	0.97	0.93	0.97	0.96	0.96
	RMSE (°C)	4.18	5.46	3.84	3.48	5.37	3.35	3.78	4.21

A descriptive statistical analysis of NARR precipitation along with the D3 onsite station precipitation for 2003 and 2004-2006 (calibration year and validation years, respectively for subsequent modeling) (Table 4-4) shows the NARR dataset tends to underestimate maximum values of precipitation and overestimate cumulative annual

precipitation. A comparison of the observed D3 onsite station and the NARR precipitation values indicates that the observed and the NARR precipitation datasets, for the validation years, contain a large number of zero values (dry days) (Figure 4-2); indicating a strongly skewed distribution. Two reasons for non-normality are the presence of outliers (high-intensity precipitation events relative to the large number of dry days) and the nature of the precipitation distribution in semi arid regions (almost 67 % of rainfall occurs from June to August and is delivered largely as convective storms of high intensity and short duration (Carey, 2008)). In this case, the relatively small number of high-intensity precipitation events distorts the results; subsequently, calculating the mean is misleading thus, statistical tests based on the normal distribution would give meaningless interpretation of the data. As a result, the precipitation data series were transformed log-normally to reduce the effect of non-normality; as well, a constant (offset of 1.0) was added to the precipitation data series to ensure that the log-transformation will have the optimal effect on the datasets. Table 4-4 shows average mean values of 0.29 and 0.25, for the validation years, for the NARR and the D3 onsite station, respectively. The average standard deviation and skewness values of the NARR precipitation are 0.69 and 2.17, respectively. Similarly, these values are 0.63 and 2.84 for the D3 onsite station.

Kendall's non parametric test was conducted on the NARR daily precipitation and the onsite precipitation. The analysis showed a Kendall's coefficient of concordance of 0.024 for the two precipitation datasets, which reflects statistically significant differences between the two precipitation series. Mesinger et al. (2003) reported that NARR precipitation is assimilated using latent heat information derived from

observations. Thus, it was not possible to achieve such exceedingly good agreement over land, however, the agreement is still reasonable in magnitude but not in the detailed distribution. The results showed that the NARR dataset tends to underestimate maximum values of precipitation which might be one reason for the inferior correlation coefficient between the two precipitation datasets.

Table 4-4 Descriptive statistical properties of precipitation for the NARR and D3 station datasets.

Statistics	NARR				Onsite station			
	2003	2004	2005	2006	2003	2004	2005	2006
Maximum	18.7	20.2	23.2	25.65	26.8	23.4	25.2	43.7
Mean	0.52	0.27	0.29	0.31	0.42	0.23	0.28	0.23
Standard deviation	0.68	0.68	0.73	0.67	0.68	0.60	0.66	0.62
Skewness	1.54	2.33	2.19	1.99	1.74	3.00	2.52	3.01
Cum. Precipitation	475.3	330.9	384.6	330.8	413.1	278.2	341.2	294.3

The descriptive statistical analysis for the SWSS site shows a cumulative annual precipitation value of 372.8 mm for the calibration year (2003), and 285.9 and 322.1 mm for 2005 and 2006, respectively. The NARR dataset overestimated the cumulative annual precipitation for 2003 and 2005 but underestimated the cumulative precipitation for 2006.

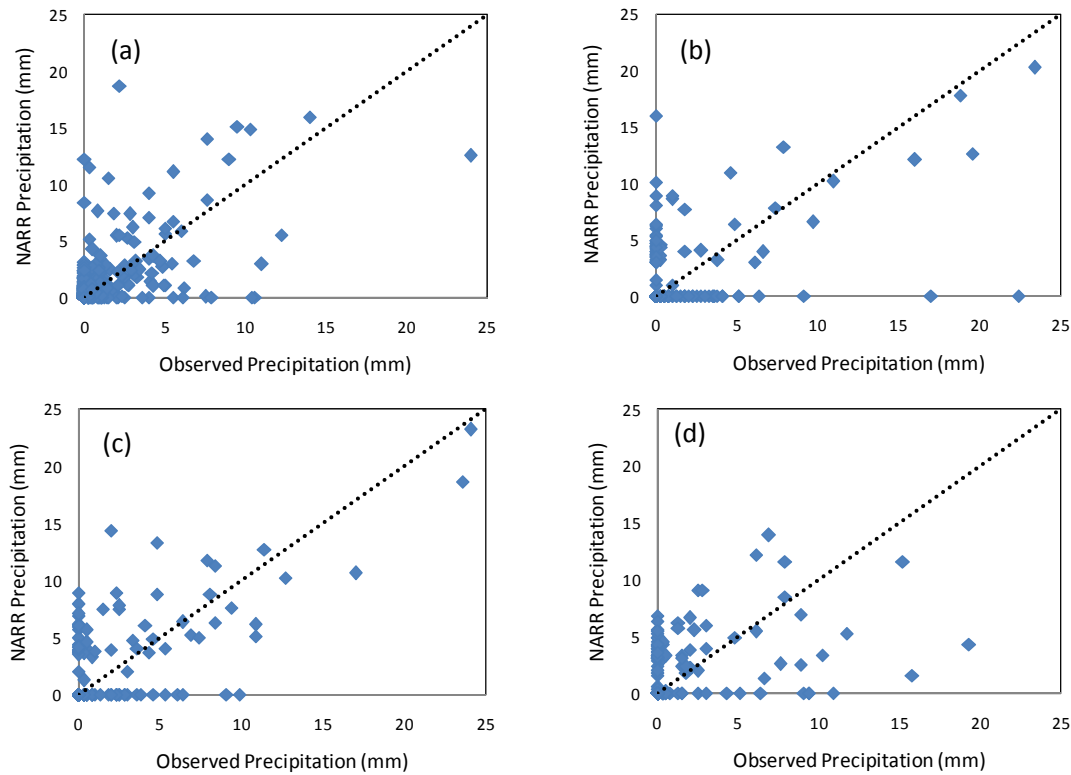


Figure 4-2 Observed D3 cover and NARR precipitation: (a) calibration year 2003; and (b-d) validation years 2004-2006.

4.4.3 GSDW model simulation results

4.4.3.1 D3 cover hydrologic performance

The SS-calibrated daily soil moisture storage for calibration year (2003) was in good agreement with the observed data in trend and in magnitude for the D3 cover (Figure 4-3); with an average MARE value of 6 % for the top and subsequent layer. The model provided an average RMSE value of ± 3.2 mm away from the mean for both layers. The SS-calibrated GSDW model captured the general trend of the soil moisture in the D3 cover, especially for the surface layer where R ranged from 0.65 to 0.78 in the validation

period (Table 4-5). The subsurface till layer showed a relatively low correlations ranging from 0.52 to 0.76 for 2004 and 2005, respectively, and a negative correlation for 2006. Overall, the average MARE values for the D3 cover were 9 and 4% for the top and subsequent layer, respectively.

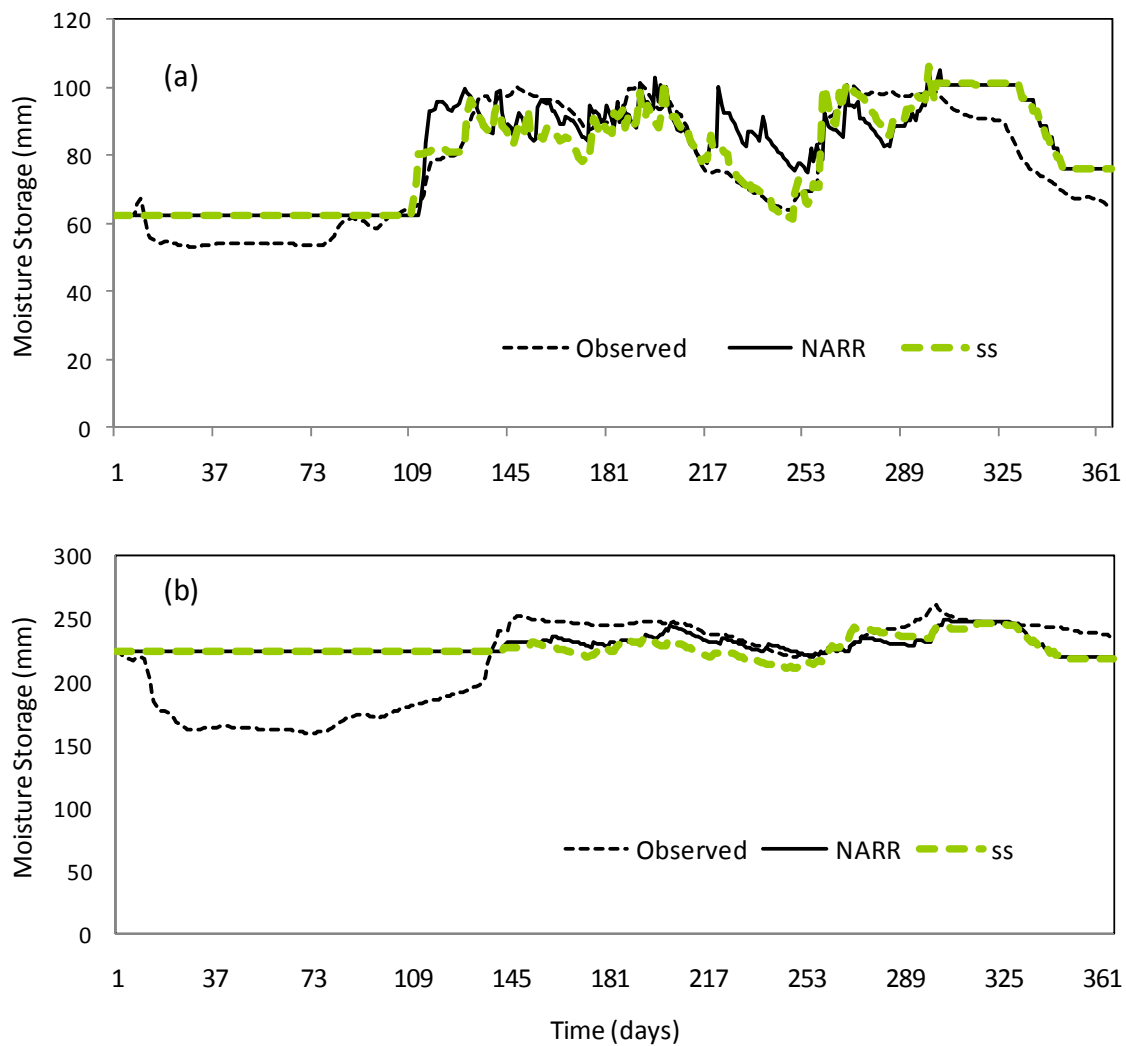


Figure 4-3 Daily simulated soil moisture storage for the calibration period (2003) using both models along with observed soil moisture for the D3 cover: (a) peat layer and (b) till layer.

Table 4-5 Performance statistics of the GSDW model regarding soil moisture during the validation period.

Site	Dataset	Layer	Year	MARE (%)	RMSE (mm)	R
D3 ^a	SS	Peat	2004	9	2.9	0.78
			2005	9	2.9	0.73
			2006	9	2.9	0.65
		Till	2004	4	3.6	0.52
			2005	4	3.5	0.76
			2006	4	3.6	-0.39
D3 ^b	NARR	Peat	2004	9	2.9	0.65
			2005	9	3.0	0.47
			2006	9	2.9	0.55
		Till	2004	4	3.6	0.53
			2005	4	3.7	0.89
			2006	4	3.4	0.41
SWSS ^a	SS	Till	2005	5	2.9	0.49
			2006	6	3.0	0.44
		Tailing sand	2005	10	4.6	0.45
			2006	8	4.1	0.31
SWSS ^b	NARR	Till	2005	8	3.5	0.62
			2006	7	3.2	0.65
		Tailing sand	2005	12	5.1	0.04
			2006	8	4.1	0.47

^a GSDW model calibrated using onsite weather station data; ^b Model calibrated using NARR precipitation and temperature; remaining data obtained from onsite weather station.

The simulated soil moisture storage in the top layer was in good agreement with the observed values (Figure 4-4), with a tendency to overestimate peak values of soil moisture pattern for the top layer.

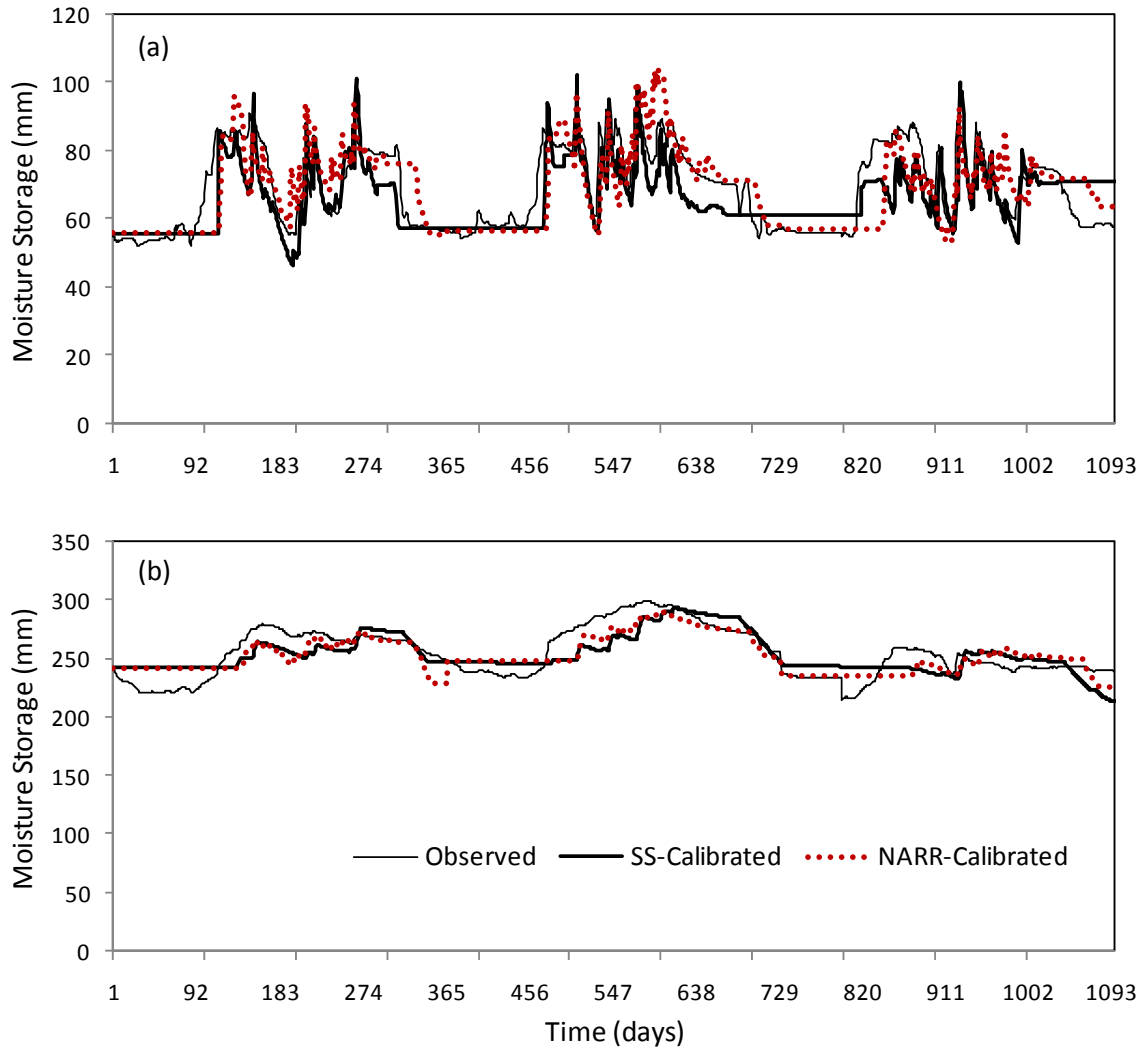


Figure 4-4 Daily simulated soil moisture storage for the validation period (2004-2006) along with observed soil moisture for the D3 cover: (a) peat layer and (b) till layer.

The GSDW model was recalibrated using NARR data showing an average MARE value of 6 % and an average RMSE of 3.2 mm for both layers (Figure 4-3). For the D3 cover, R values ranged from 0.47 to 0.65 in the peat layer; whereas in the till layer, R values were 0.53 in 2004, 0.89 in 2005, and 0.41 in 2006. Average MARE values were 9 and 4% in the peat and till, respectively. Over both layers, the model provided an

average RMSE value of ± 3.3 mm away from the mean soil moisture value. The daily soil moisture storage for validation years (2004-2006) were in good agreement with the observed data in trend and in magnitude for the D3 cover (Figure 4-4).

All simulations were generally effective in capturing soil moisture dynamics during the growing seasons; however, the agreement among those patterns was not as good for the spring and fall periods. Onsite precipitation in 2005, mostly occurring between days 580 and 655 (Figure 4-4), resulted in underestimating the D3 soil moisture storage during this period compared to the observed values (Figure 4-4). Precipitation data showed cumulative values of 101.2 and 75.9 mm during the same period for NARR and onsite station, respectively. For the D3 cover, the SS-calibrated model was not able to reproduce the soil moisture storage during the snowmelt period of 2006 compared to the NARR-calibrated model. Comparing precipitation datasets from both sources during winter period (Oct. 2005 to March 2006) and trying to link them to the observed soil moisture storage, the comparison showed that the accumulated snow were 55.8 and 12.2 mm from NARR and onsite weather station, respectively. However, the observed soil moisture pattern in Figure 4-4 showed an increase of 22 mm in moisture storage associated with the same snowmelt event, which raises a serious question about the uncertainty associated with the onsite measured data.

4.4.3.2 SWSS watershed hydrologic performance

For the SWSS site, the simulated soil moisture storage values for 2003 (calibration year) was in good agreement with the observed data (Figure 4-5). For the top

and tailing sand layer, average MARE values were 5 and 9 %, and average RMSE values were 2.8 and 4.6 mm, respectively.

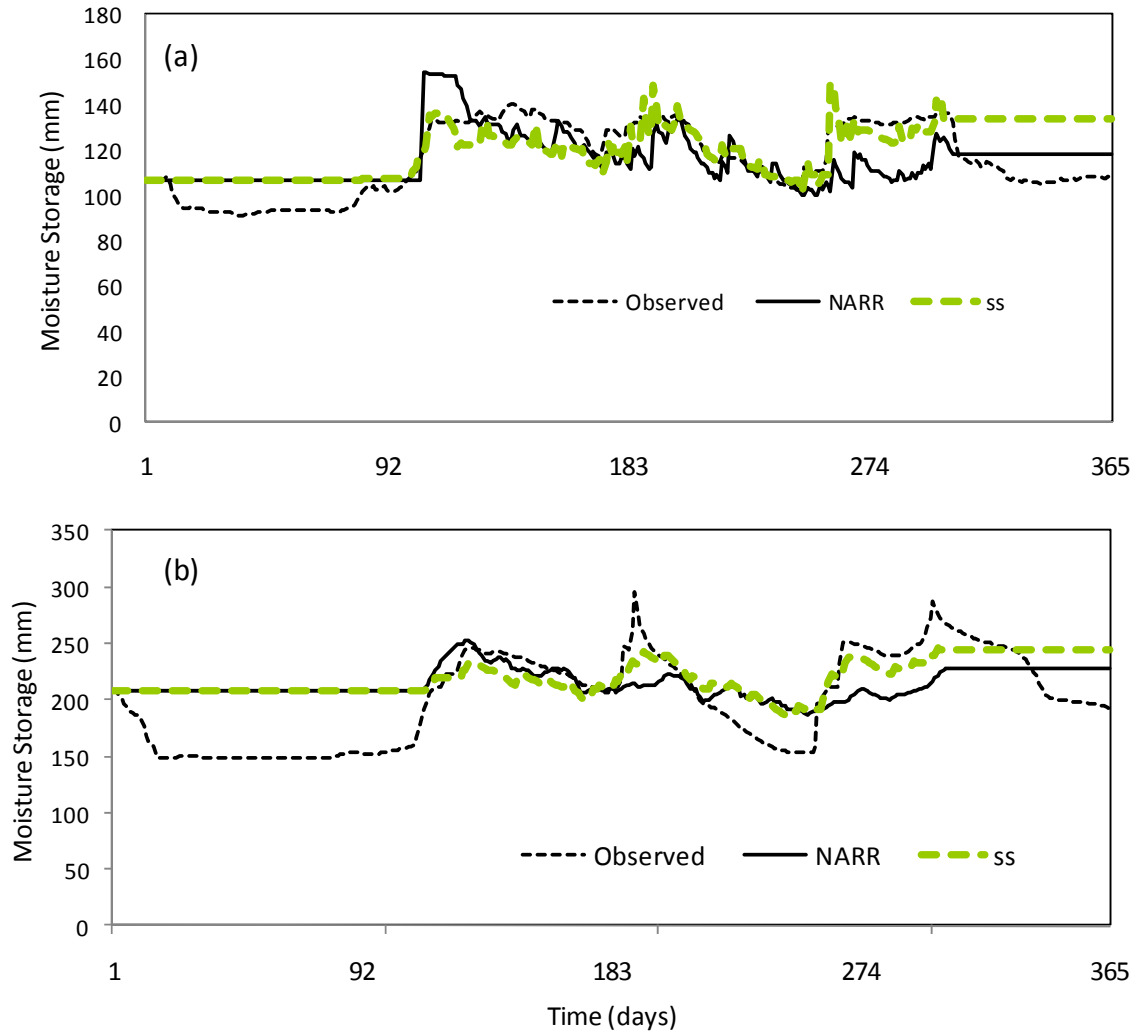


Figure 4-5 Daily simulated soil moisture storage for the calibration period (2003), for both models, along with observed soil moisture for the SWSS site: (a) till layer and (b) tailing sand layer.

The simulated soil moisture storage values for 2005 and 2006 (validation years), based on the SS-calibrated model along with the observed soil moisture, were in good agreement with the observed data (Figure 4-6). The average correlation coefficient was

0.49 for the top layer; the subsurface layer showed relatively low correlations of 0.45 and 0.31 for 2005 and 2006, respectively (Table 4-5). For the top and tailing sand layer, average MARE values were 6 and 10%, and average RMSE values were 3.0 and 4.5 mm, respectively. The GSDW model was recalibrated using NARR data for the SWSS site. For the top and subsequent layer, average MARE values were 8 and 10%, and average RMSE value of 4.4 mm for both layers, respectively. The average correlation coefficients for the validation years were 0.63 and 0.25 for the top and subsequent layer, respectively; corresponding MARE values were 7 and 10%. The average RMSE value for both layers was ± 4 mm of soil moisture. The simulated daily soil moisture storage for the validation years (2005-2006) were in good agreement (in trend and magnitude) with the observed soil moisture values, especially for the top layer (Figure 4-6), which is the most important for vegetation growth.

The GSDW model efficiently reproduced the magnitude and the trend of soil moisture peak patterns using both datasets, especially for the top layer. Conversely, the SWSS SS-calibrated model captured a substantial increase in the simulated soil moisture storage at day 560 compared to the observed values (Figure 4-6). Onsite precipitation at the previous day, recorded an intense precipitation event of 46.2 mm, resulted in a substantial increase in the simulated soil moisture storage. For the SWSS watershed, precipitation series showed high inconsistency, in timing and in magnitude, occurring in 2005 between days 150 and 183 of 100.6 and 55.3 mm for the onsite station and NARR data, respectively. As a result, NARR-calibrated model underestimated the SWSS soil moisture storage compared to the SS-calibrated model (Figure 4-6).

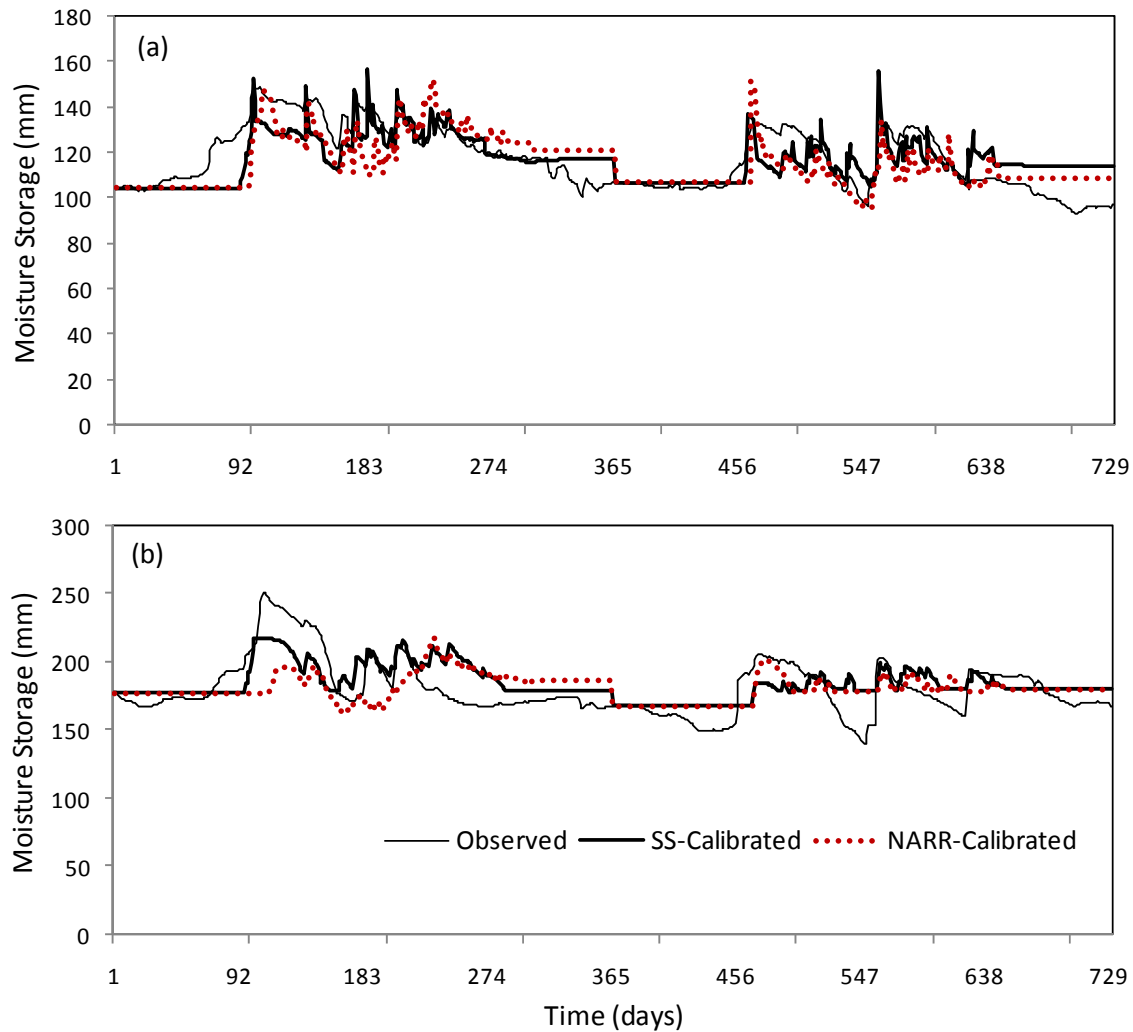


Figure 4-6 Daily simulated soil moisture storage for the validation period (2005-2006) along with observed soil moisture for the SWSS site: (a) till layer and (b) tailing sand layer.

In general, the performance of the NARR-calibrated GSDW model in simulating soil moisture storage was better in the D3 cover than at the SWSS site. The inferior performance of the model in the latter case is attributed to inconsistencies between the SWSS onsite precipitation values and the NAAR-precipitation in timing and in magnitude (e.g. descriptive analysis for the SWSS site indicated onsite precipitation was

almost 25% less than NARR precipitation for 2005). Figure 4-7(a-b) shows scatter plots of simulated daily AET values vs. observed daily AET for both the D3-cover and the SWSS site during the growing season. Relatively, the D3 watershed AET has less scatter than the SWSS AET flux. The inconsistencies between the NARR-AET and the observed SS-AET fluxes, in both watersheds, were due to the differences between the two datasets (air temperature and precipitation) in trend and magnitude. For the D3 cover, the model provided overall average values of RMSE and R of 1.0 mm and 0.23, respectively. For the SWSS, the corresponding values were 1.48 mm and 0.25. Figure 4-7(c-d) shows correlation plots of the simulated potential evapotranspiration (PET) in both watersheds based on SS- and NARR-calibrated models. Relatively, PET on the SWSS site has less scatter than that on the D3 site. The scatter plot indicated a high variability of NARR air temperature dataset compared to the onsite station air temperature in D3 cover. For the SWSS watershed, the NARR-calibrated model was able to estimate PET more consistently with the SS-calibrated model. This might be attributed to the reason that the SWSS watershed air temperature from both datasets was in better agreement. Figure 4-7(c-d) shows a tendency of the NARR-calibrated models to overestimate the simulated PET flux, in D3 cover, due to the warm bias of NARR air temperature dataset. The models provided overall average R values of 0.67 to 0.97 for the D3 and the SWSS watersheds-simulated PET, respectively.

Runoff events are rare in those reconstructed prairie watersheds except for snowmelt period only. In general, the onsite and the NARR datasets reproduced surface runoff with slight differences in 2005 in both sites; however, the simulated surface runoff

values, based on both datasets, were not in good agreement for 2004 and 2006 in D3 cover. For the D3 cover, the reproduced surface runoff values were 16 and 34 mm in 2004, as well as, 3 and 37 mm in 2006 for SS- and NARR-calibrated models, respectively.

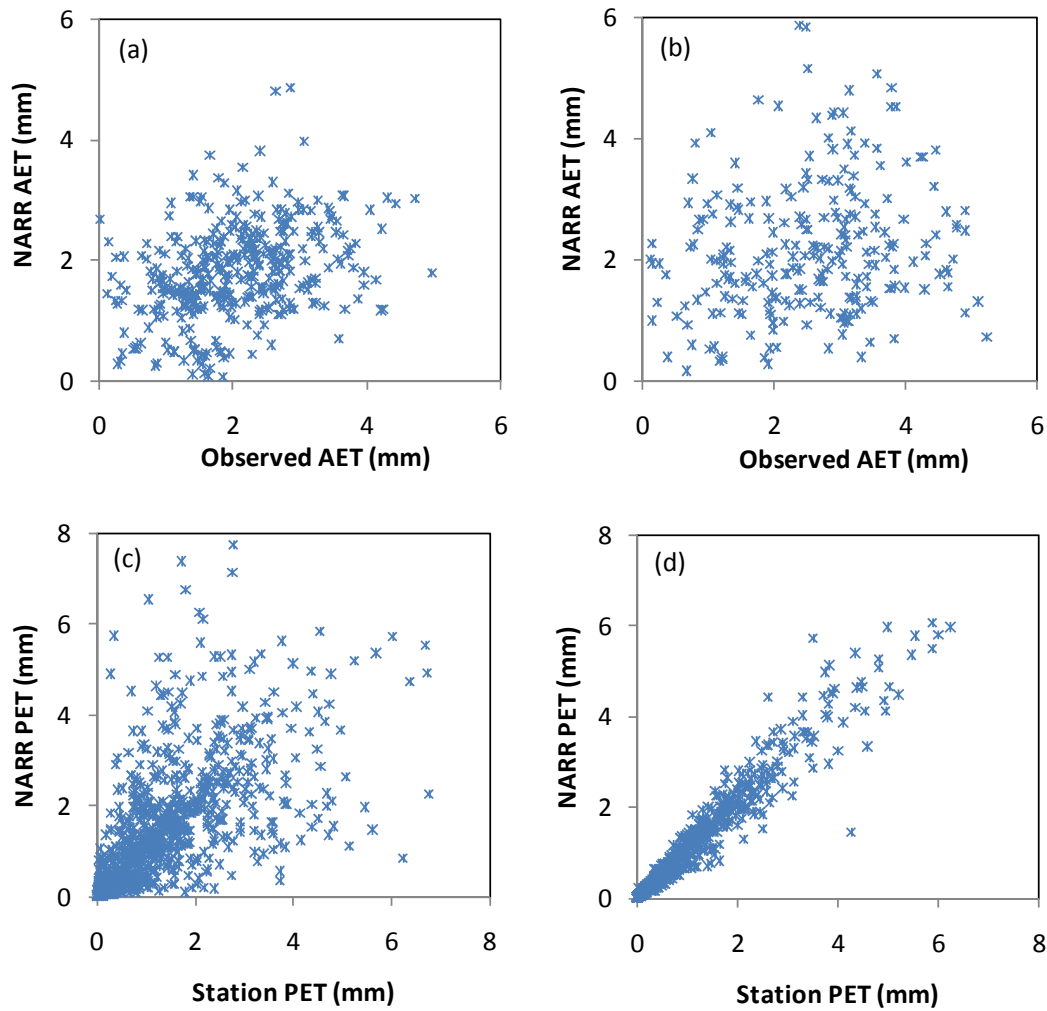


Figure 4-7 Simulated-NARR and observed daily ET flux values: (a) D3 cover AET flux (2004-2006); (b) SWSS watershed AET flux (2005-2006); (c) D3 cover PET (2004-2006); (d) SWSS watershed PET (2005-2006).

4.4.4 Long term probabilistic assessment of the hydrological performance of reconstructed watersheds

The NARR-calibrated model was used along with the NARR long term dataset (1979-2006) to evaluate the current/future hydrological performance of existing reconstructed watersheds with respect to soil moisture deficit using a probabilistic framework, and the results compared with long term performance estimates using the onsite-calibrated GSDW model. For both datasets, the best distribution for the D3 cover (Figure 4-8) was found to be InvGauss (inverse Gaussian or Wald) distribution, where μ and λ are the mean and shape parameters, respectively (Palisade Corporation, 2005). A few instances occurred when the D3 cover had negative values of D_m , indicating surplus water. Positive values of D_m contribute to water requirements such as vegetation requirements and evaporation needs. According to the EC and NARR datasets, the D3 cover at the 90% non-exceedance probability might be able to store and release up to 135 and 146 mm of moisture, respectively. At a non-exceedance probability of 90%, this cover would only be required to store-and-release this amount of moisture holding capacity ten times in 100 years. The D3-NARR D_m shows a tendency to store and release moisture under the stress of high water requirements ($\geq 80\%$ non-exceedance probability) compared to the D3-EC maximum moisture deficit. For the D3 cover, the D_m distributions were determined to be:

Soil cover D3-EC (100 cm); InvGauss(351.1, 23998.6) Shift=-271.6

Soil cover D3-NARR (100 cm); InvGauss(135.71, 825.82) Shift=-62.493

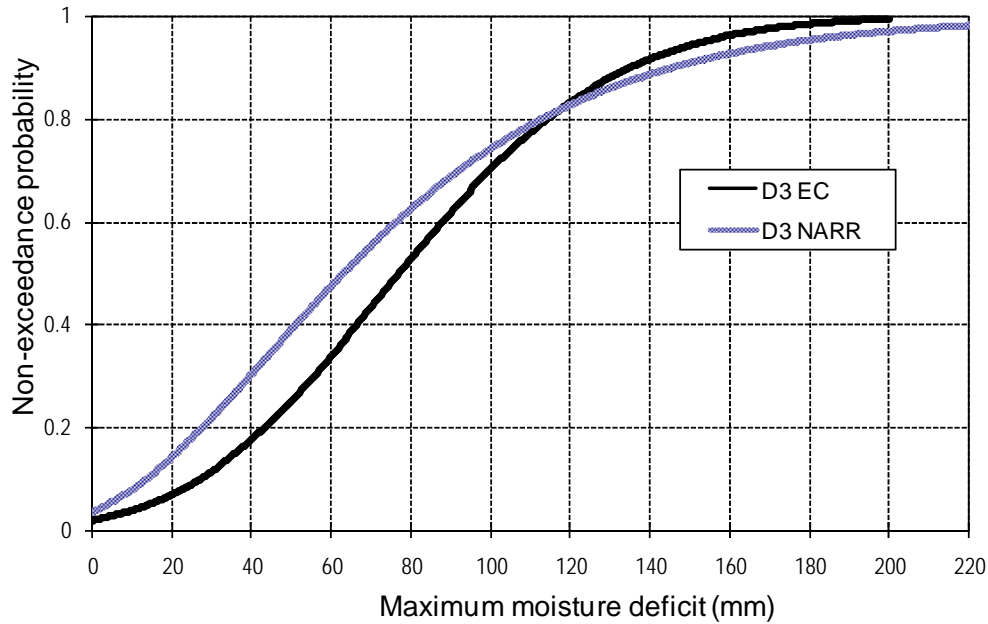


Figure 4-8 Stochastic comparison of the hydrological performance of the D3 cover based on EC and NARR datasets.

The best distribution for the SWSS watershed was found to be normal (μ , σ), where μ and σ are the mean and standard deviation of the distribution. The fitted distributions for SWSS-EC and SWSS-NARR (Figure 4-9) reveal the NARR dataset is shifted to the right compared to EC dataset, which indicates a tendency to store and release soil moisture under high stress demand. The SWSS watershed showed the ability to store and release up to 117 and 127 mm of moisture at the 90% non-exceedance probability using EC and NARR datasets, respectively. For the SWSS watershed, the D_m distributions were determined to be:

SWSS-EC site; Normal(61.2, 43.2)

SWSS-NARR site; Normal(71.1, 43.7)

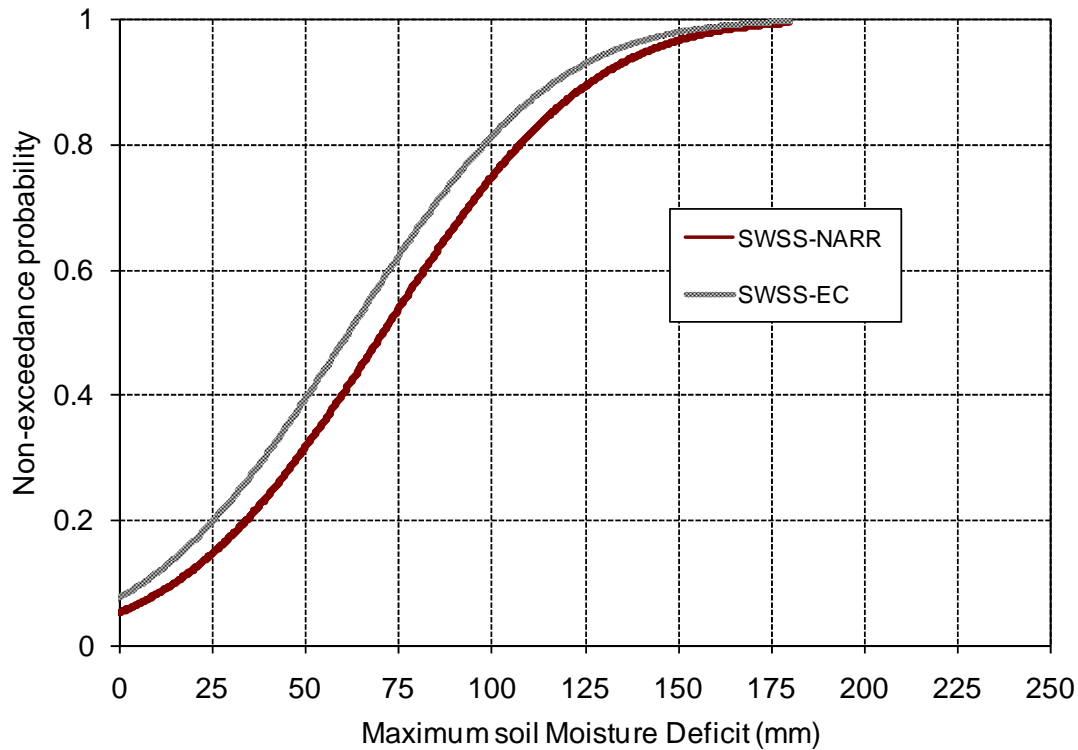


Figure 4-9 Stochastic comparison of the hydrological performance of the SWSS watershed based on EC and NARR datasets.

A stochastic comparison for the D3 cover (Figure 4-8) shows that, up to the frequency of 81% (D_m Value of 118 mm), the cover has more moisture store and release ability than indicated by the D3-NARR curve. This finding concurs with results indicating a tendency for the SS-calibrated model to overestimate peak values of soil moisture patterns in the D3 cover compared to the NARR-calibrated model; these peaks were followed by moisture depletion, which indicate an increase of the D3-EC moisture deficit values. This indication is reversed at extreme conditions (beyond the 81% non-exceedance probability). In general, the inconsistency of timing, location, and intensity of

precipitation events between the two datasets affects the moisture dynamic patterns in the soil, which in turn affects the daily moisture deficit in value and trend. For the SWSS site (Figure 4-9), the NARR frequency curve is shifted slightly to the right compared to the SWSS-EC frequency curve. The average annual long term precipitation was 455.8 mm based on the climate data from Environment Canada meteorological station at Fort McMurray, but only 424.5 mm based on the NARR long term dataset. The shift could be attributed to NARR reanalysis underestimating the average annual long term precipitation compared to the EC weather station, resulting in a tendency to increase store and release abilities (needs). Again, the discrepancies likely stem from dataset differences resulting from NARR data representing aerial averages and Environment Canada weather station datasets representing point measurements.

4.5 Conclusions

This study confirmed the utility of precipitation and temperature data from the North American Regional Reanalysis (NARR) for the hydrological modeling of reconstructed watersheds. With the current rate of oil sands industry expansion, there is a need to establish a platform of acquiring the data other than local onsite weather stations which needs continuous efforts in setting up and maintaining. The present study has demonstrated that NARR temperature and precipitation data are viable alternative to onsite weather station for future reclaimed sites in the same study area.

The GSDW model, re-calibrated using NARR data, produced results similar to the model calibrated with onsite weather station data. Correlations between the data sets

for precipitation values were less than for temperature values, which was attributed to NARR data representing aerial averages that assimilate observed weather information into a numerical weather forecast system along with topography and land cover information vs. weather station data representing point measurements. The NARR long term dataset (1979-2006) was successfully implemented in a probabilistic framework to assess the hydrological performance of two reconstructed watersheds with respect to soil moisture deficit. The simulations indicate the D3 cover is able to release more moisture under high water requirements than the SWSS site. The D3 cover also showed a tendency to store and release more moisture under high demands using the NARR dataset than the EC data. This slight variance might be due to precipitation discrepancies between both datasets in intensity and in timing. Overall, the results indicate the reconstructed watersheds studied have a high probability of providing the threshold of soil moisture essential for vegetation recovery.

NARR contains almost every atmospheric variable (e.g., precipitation, temperature) required for modeling hydrological processes. Our results clearly demonstrate the merits of using NARR data for hydrological modeling, especially in cases of data scarcity and in remote regions. However, while NARR data may substantially assist with overcoming the scarcity of weather stations, data from conventional platforms (e.g., meteorological stations) are essential to validate the NARR datasets. Our novel application of NARR data for the purpose of evaluating the current/future hydrological performance of existing reconstructed watersheds demonstrates their utility for simulating hydrological processes (e.g., soil moisture

storage, evapotranspiration). Moreover, adopting NARR data for the assessment of the long term hydrological performance of reconstructed watersheds can inform decision making with respect to the design of reconstructed soil covers.

4.6 Acknowledgements

The authors acknowledge the financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC), the Cumulative Environmental Management Association (CEMA), the Egyptian government scholarship program, and the Department of Civil and Geological Engineering, University of Saskatchewan, Canada.

4.7 References

- Amenu, G.G. and P. Kumar, 2008. A model for hydraulic redistribution incorporating coupled soil-root moisture transport. *Hydrology and Earth System Sciences*, 12:55–74.
- Anderson, E.A., 1976. A point energy and mass balance of a snow cover. NOAA Tech. Rept. NWS 19, U.S. Dept. of Commerce, Washington, D.C.
- Barbour, S.L., D. Chapman, C. Qualizza, S. Kessler, C. Boese, R. Shurniak, G. Meiers, M. O’Kane, J. Hendry and S. Wall, 2004. Tracking the evolution of reclaimed landscapes through the use of instrumented watersheds – a brief history of the Syncrude Southwest 30 Overburden Reclamation Research Program. *Proceedings of the International Instrumented Watershed Symposium, Edmonton, Canada*, www.rr.ualberta.ca/oilsands/IIWS.htm.

- Boese, K., 2003. The design and installation of a field instrumentation program for the evaluation of soil-atmosphere water fluxes in a vegetated cover over saline/sodic shale overburden. *MSc Thesis, University of Saskatchewan, Saskatoon, Saskatchewan, Canada*, 169 pp.
- Carey, S.K., 2008. Growing season energy and water exchange from an oil sands overburden reclamation soil cover, Fort McMurray, Alberta, Canada. *Hydrological Processes*, 22:2847–2857.
- Choi W., S.J. Kim, P.F. Rasmussen and A.R. Moore, 2009. Use of the North American Regional Reanalysis for Hydrological Modelling in Manitoba. *Canadian Water Resources Journal*, 34(1):17–36.
- Costanza, R., and M. Ruth, 1998. Using dynamic modeling to scope environmental problems and build consensus. *Environmental Management*, 22(2):183–195.
- Elshorbagy A., A. Jutla and J. Kells, 2007. Simulation of the hydrological processes on reconstructed watersheds using system dynamics. *Hydrological Science Journal*, 52(3):538–561.
- Elshorbagy, A. and S.L. Barbour, 2007. A probabilistic approach for design and hydrologic performance assessment of reconstructed watersheds. *Journal of Geotechnical & Geoenvironmental Engineering ASCE*. 133(9):1110–1118.
- Elshorbagy, A., A. Jutla, L. Barbour and J. Kells, 2005. System dynamics approach to assess the sustainability of reclamation of distributed watersheds. *Canadian Journal of Civil Engineering*, 32:144–158.

- Finnigan JJ, R. Clement, Y. Mahli, R. Leuning, and HA. Cleugh, 2003. A re-evaluation of long term flux measurement techniques part I: Averaging and coordinate rotation. *Boundary. Layer Meteorology*, 107:1-48.
- Gerwin, W., T. Raab, D. Biemelt, O. Bens and R.F. Huttl, 2009. The artificial water catchment “Chicken Creek” as an observatory for critical zone processes and structures. *Hydrology and Earth System Sciences Discussions*, 6:1769–1795.
- Green, W.H., and G.A. Ampt., 1911. Studies on soil physics, part I, the flow of air and water through soils. *Journal of Agricultural Science*, 4(1): 1-24.
- Gilley, J.E., G.W. Gee, A. Bauer, W.O. Willis and R.A. Young, 1977. Runoff and erosion characteristics of surface mined sites in western North Dakota. *Transactions of American Society of Agricultural Engineers*, 20(4):697–704.
- Haberlandt, U. and G.W. Kite, 1998. Estimation of daily space-time precipitation series for macroscale hydrological modelling. *Hydrological Processes*, 12:1419–1432.
- Haigh, M.J., 2000. The aims of land reclamation, *Land Reconstruction and Management. A. A. Balkema Publishers, Rotterdam, The Netherlands*, 1:1–20.
- High Performance Systems Inc (HPS), 2001. Tutorial and technical documentation: STELLA® II, High Performance Systems Inc., Hanover, N.H. [now ISES Systems, Lebanon, N.H.].
- Julta, A.S., 2006. Hydrologic modeling of reconstructed watersheds using a system dynamics approach. *M.Sc. Thesis, University of Saskatchewan, Canada*, 139 pp.
- Keshta, N., A. Elshorbagy and S. Carey, 2009. A generic system dynamics model for simulating and evaluating the hydrological performance of reconstructed watersheds. *Hydrology and Earth System Sciences*, 13(6):865–881.

- Kidwell, K.B, 1995. NOAA Polar Orbiter data user's guide, U.S. Dept. of Commerce, NOAA/NESDIS, Washington, DC, 410 pp.
- Li, L. and S.P Simonovic, 2002. System dynamics model for predicting floods from snowmelt in North American prairie watersheds. *Hydrological Processes*, 16:2645–2666.
- Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P.C. Shafran, W. Ebisuzaki, D. Jovid, J. Woollen, E. Rogers, E.H. Berbery, M.B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish and W. Shi, 2006. North American Regional Reanalysis. *Bulletin of the American Meteorological Society*, 87:343–360.
- Mesinger, F., G. DiMego, E. Kalnay, P. Shafran, W. Ebisuzaki, Y. Fan, R. Grumbine, W. Higgins, Y. Lin, K. Mitchell, D. Parrish, E. Rogers, W. Shi, D. Stokes and J. Woolen, 2003. NCEP Regional Reanalysis. Symp. on observing and understanding the variability of water in weather and climate. paper 5.7, Combined Preprints CD-ROM, 83rd AMS Annual Meeting, Long Beach, CA.
- Nigam, S. and A. Ruiz-Barradas, 2006. Seasonal hydroclimate variability over North America in Global and Regional Reanalyses and AMIP Simulations: Varied representation. *Journal of Climate*, 19:815–837.
- Palisade Corporation Inc. 2005. Guide to Using @RISK. Advanced risk analysis for spreadsheets. Palisade Corporation, NY, U.S.A.
- Parasuraman, K., A. Elshorbagy and S.K. Carey, 2007. Modelling the dynamics of the evapotranspiration process using genetic programming. *Hydrological Sciences Journal*, 52(3):563–578.

- Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. *Proc. Roy. Soc. London A*(194), S. 120-145.
- Rao, V.B., C.E. Santo and S.H. Franchito, 2002. A diagnosis of rainfall over South America during the 1997/98 El Niño event. Part I: validation of NCEP–NCAR reanalysis rainfall data. *Journal of Climate*, 15(5): 502–511.
- Reid, P.A., P.D. Jones, O. Brown, C.M. Goodess, and T.D. Davies, 2001. Assessment of the reliability of NCEP circulation data and relationships with surface climate by direct comparisons with station based data. *Climate Research*, 17:247-261.
- Shafran, P., J. Woollen, W. Ebisuzaki, W. Shi, Y. Fan, R.W. Grumbine and M. Fennessy, 2004. Observational data used for assimilation in the NCEP North American Regional Reanalysis, *20th Intl. Conf. on Interactive Information Processing Systems for Meteorology, Oceanography and Hydrology*. Seattle, WA, 11-15 Jan 2004.
- Shepard, D., 1968. A two-dimensional interpolation function for irregularly-spaced data. *Proceedings of the 1968 Association of Computing Machinery National Conference*: 517–524. doi:10.1145/800186.810616
- Tolika, K., P. Maheras, H.A. Flocas and A. Arseni-Papadimitriou, 2006. An evaluation of a general circulation model (GCM) and the NCEP/NCAR reanalysis data for winter precipitation in Greece. *International Journal of Climatology*, 26:935–955.
- Trenberth, K.E. and C.J. Guillemot, 1998. Evaluation of the atmospheric moisture and hydrological cycle in the NCEP/NCAR reanalyses. *Climate Dynamics*, 14:213–231.
- Van Dijk, A.I.J.M. and L.A. Bruijnzeel, 2001. Modelling rainfall interception by vegetation of variable density using an adapted analytical model. Part 1: model description. *Journal of Hydrology*, 247:230–238.

- van Genuchten, M. Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, 44:892–898.
- Woo, M.K. and R. Thorne., 2006. Snowmelt contribution to discharge from a large mountainous catchment in subarctic Canada. *Hydrological Processes*, 20:2129–2139.
- Xie, P., and P.A. Arkin, 1997. Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bulletin of the American Meteorological Society*, 78:2539–2558.

Chapter 5 - Impacts of Climate Change on Soil Moisture and Evapotranspiration in Reconstructed Watersheds

This has been prepared for publication as a research paper in the *Hydrological Processes Journal*.

Contribution of the PhD candidate

Model conceptualization was carried out by the candidate and the second author. Simulations were performed by the candidate, with the second author providing guidance at various stages of the work. The third author helped to obtain the dataset used in this study and also reviewed the manuscript. The manuscript was drafted by the candidate with critical editing and technical review provided by the second author.

Contribution of this chapter to the overall study

The objective of the article upon which this chapter is based was to assess the impact of projected climate change on the hydrological performance (soil moisture dynamics and evapotranspiration) of the reconstructed watersheds. This chapter is a continuation of the use of the generic systems dynamic watershed (GSDW) model developed in Chapter 2 and the probabilistic framework adopted in Chapters 3 and 4. In this chapter, the GSDW model was applied to three watersheds using climate scenarios generated from daily precipitation and air temperature output of global climate models (CGCM3), under A2 and B1 emission scenarios, to simulate the corresponding soil

moisture. Moisture deficit frequency curves were subsequently constructed. The predicted maximum moisture deficits based on A2 and B1 emission scenarios are expected to decrease compared to the moisture deficit predicted using the historical meteorological record. The decrease in moisture deficit associated with A2 and B1 emission scenarios were attributed to the expected increase in precipitation rates; actual evapotranspiration was expected to increase.

5.1 Abstract

This study aims at developing a generalized understanding of the sensitivity of soil moisture patterns in reconstructed watersheds, in northern Alberta, to changes in the projected precipitation in the 21st century. The GSDW model is applied to three watersheds using climate scenarios generated using daily precipitation and air temperature output from a global climate model (CGCM3), under A2 and B1 emission scenarios, to simulate the corresponding soil moisture. CGCM3 results indicate an increase in the mean annual temperature for Fort McMurray, Alberta of 3.3 (A2) and 2.4 °C (B1), and an increase in the predicted annual precipitation of 34% (A2) and 8.6% with A2 and B1 emission scenarios, respectively. The GSDW model is used, along with on-site historical data, to downscale A2 and B1 emission scenarios and evaluates the future hydrological performance of the designated watersheds with respect to soil moisture deficit and actual evapotranspiration using a probabilistic framework. The forecasted maximum soil moisture deficit values based on A2 and B1 emission scenarios are expected to decrease compared to those based on the current, largely due to the expected increase in precipitation rates, associated with an expected increase in evapotranspiration.

5.2 Introduction

Oil sands deposits were discovered over 100 years ago in the boreal forest region of northern Alberta, Canada. This region is a complex mosaic of forests and wetlands comprising approximately 140,000 km² and provides many ecosystem services such as water and carbon storage and as a host for numerous species of unique plants and

wildlife. Beginning in the 1960s, oil sands mining has occurred in this region, and now affects approximately 3400 km² of surface area. The Canadian association of petroleum producers predicted that Canadian oil sands production would grow from 1.2 million barrels per day in 2008 to 3.3 million barrels per day in 2020 (CAPP, 2008b). With the current rate of oil sands industry expansion, the effect of mining activities on the ecological functions is not restricted only to deforestation and removing the overburden materials to gain access to the oil-bearing formations, but it is also intensified by the large deposits of toxic chemicals, polluted water during the separation process, and the emission of carbon dioxide and other gases. Boreal forests are the largest terrestrial carbon reservoir in the world; storing approximately 22% of the total carbon in the planet's land surfaces (IPCC, 2000). The oil sands make up 5% of Canada's greenhouse gas emissions, and this amount is anticipated to increase to 8% by 2015 (CAPP, 2008a).

Considering the current rate of oil sands development, and as a condition to gain government consent to commence mining activity, the Canadian oil sands industry is required to implement a reclamation plan to restore mining pits to “equivalent land capability” (Gilley et al., 1977). In this framework, reconstructed (reclaimed) land should be able to support various land uses after reclamation similar to what existed before mining. The mining industry aspires to create a complex of boreal forests and wetlands that will eventually colonize the reconstructed landscapes; however, experience has shown that characterizing and adopting a particular sustainable reconstructed alternative is a daunting task because of the high nonlinearity embedded within the reconstructed systems.

Several studies have been conducted on oil sands reconstructed watersheds using system dynamics models, providing insight on the current hydrological behaviour of those systems (Elshorbagy et al., 2005; Julta, 2006; Elshorbagy and Barbour, 2007; Keshta et al., 2009). However, in pursuit of improving an assessment tool of reconstructed sites, Elshorbagy and Barbour (2007) proposed a probabilistic framework to assess the hydrological performance of the reconstructed soil covers based on the annual maximum soil moisture deficit index. Elshorbagy and Barbour (2007) used a calibrated site-specific system dynamics watershed model (SDW) (Elshorbagy et al., 2005; 2007), along with the Environment Canada historical meteorological records, to estimate the maximum soil moisture deficit the soil cover can sustain during the growing seasons over a 50 year period. From this, frequency curves of maximum annual soil moisture deficit were used to assess the probability that a soil cover (reconstructed watershed) can provide the desired threshold of moisture demand. In an attempt to evaluate different soil cover alternatives, further studies have been carried out to assess the hydrological performance of various reconstructed watersheds using available historical data (Elshorbagy and Barbour, 2007; Bachu and Elshorbagy, 2009; Keshta et al., 2010). Keshta and Elshorbagy (2010) used the North American Regional Reanalysis (NARR) data, instead of onsite data, to evaluate the hydrological performance of various reconstructed watersheds in comparison to natural watersheds. The adopted approach of using historical datasets was based on the hypothesis that historical meteorological record is a fair representation of possible climatic scenarios, and that the long term meteorological dataset included the different consequences of dry or wet climatic conditions. In light of possible global warming and climate change scenarios, there is a

need to develop a comprehensive assessment considering the combined and cumulative impacts arising from mining activities and possible future climate change. There is also a need to ensure that the reconstructed landscapes are self sustaining forested ecosystems that will not require ongoing maintenance in future.

The aim of this paper is to assess the potential impact of the projected climate change on the soil moisture dynamics and actual evapotranspiration on reconstructed watersheds in northern Alberta, Canada. For the purpose of this paper, the Canadian Coupled Global Climate Model CGCM3 under the A2 and B1 emission scenarios were chosen for estimating future climatic change. The assessment uses the probabilistic framework developed by Elshorbagy and Barbour (2007), and used by Keshta et al. (2010).

5.3 Global Circulation Models (GCMs)

Over the past decade, the potential impacts of climate change on the hydrological processes have received significant attention due to enhanced awareness of the cumulative impacts of global warming, and due to the advancement in the models used for forecasting the expected changes (IPCC, 2007). One method of predicting projected climate change is to use global circulation models (GCMs), which are capable of numerically simulating components of atmospheric and ocean circulation. GCMs have been developed to simulate the present climate and are used as advanced simulation tools for projecting future global warming. GCMs provide estimates of climate variables (e.g. air temperature, precipitation, wind speed, pressure, etc.) on a global scale. While they

provide acceptable prediction of large-scale circulation patterns, their coarseness of detail limit their ability to predict precipitation at smaller scales (Ghosh and Mujumdar, 2006).

The resolution of GCM outputs has hindered the assessments climate impacts as the spatial scale on which a GCM can operate (e.g. with a horizontal resolution between 250-600 km) is coarse compared to that of the hydrological processes. Therefore, downscaling techniques have to be applied to generate finer-scale horizontal distributions of climatic variables based on the coarse GCM information (Wilby and Wigley, 1997). There are two approaches for downscaling climatic variables: the dynamic approach in which the physical dynamics of the regional and local climate are solved explicitly, and the empirical (statistical downscaling) approach that uses system relationships derived from observational data (Wigley et al., 1990; Wilby and Wigley, 1997). An advantage of the statistical downscaling methods (SDSM) over the dynamic approach is their simplicity, which avoids high computational cost associated with running a regional climate model.

Several climate models and scenarios have been used to evaluate and compare different climate change outcomes for a specific region. These changes are typically compared with the normal values from 1961-1990, which is known as the GCM baseline climate. The Intergovernmental Panel on Climate Change (IPCC) has suggested 40 possible scenarios for the next century. The scenarios are split into four main categories known as the A1, A2, B1, and B2 emission scenarios based on the predictions of global population, economy, and pollutant emissions (IPCC, 2000). Each category of the special

report on emissions scenarios (SRES) includes a descriptive part called a "storyline", where each storyline assumes a distinct direction for future developments, but together they describe divergent futures that encompass a significant portion of the original uncertainties associated with each scenario.

5.4 Impacts of climate change on the hydrological processes

Numerous attempts have been made to forecast the likely changes in air temperature and precipitation patterns (e.g. Kharin and Zwiers, 2000; Groisman et al., 2005; Meehl et al., 2005; van Ulden and van Oldenborgh, 2006; Shongwe et al., 2009). A host of studies have employed hydrological models to assess the impact of climate change on runoff, and provide insight on the impacts of projected climate change on regional hydrological regimes (Bergstrom et al., 2001; Menzel and Burger, 2002; Gebremeskel et al., 2005; Cunderlik and Simonovic, 2005). For example, Kilkus et al., (2006) used the WatBal water balance model with GCMs outputs (A2 and B2 emission scenarios), in 50 river basins in Lithuania, and showed that runoff will increase slightly during the 21st century.

Merritt et al. (2006) used three GCMs with the A2 and B2 emission scenarios to estimate the projection of climate change for the Okanagan Basin in British Columbia. The study showed an increase in temperature of 1.5 - 4 °C. The predicted summer precipitation decreased by 0 - 35%, while winter precipitation is expected to increase by 5 - 20% by the 2050s. The UBC watershed model, coupled with total precipitation and temperature data derived from GCM outputs, predicted an early onset of the spring

snowmelt and considerable reductions in the annual and spring flow volumes (Merritt et al., 2006). More recently, Yonas and Coulibaly (2007) used the downscaled daily precipitation and temperature data from the Coupled Global Climate Model (CGCM1) in the WatFlood and HBV-96 model to simulate the flow regimes in the major rivers of the Saguenay watershed in Quebec. Results showed an inferior performance using both models with downscaled precipitation and temperature data in comparison with the baseline (historical) dataset, and it was recommended that downscaled meteorological variables be validated before using in climate change impact studies.

Kim et al. (2008) used the North American Regional Reanalysis (NARR) to downscale CGCM3 data, under the A2 and B1 emission scenarios (2081-2100), in two river basins in north-western Ontario, Canada. The calibrated SLURP model was used along with the downscaled CGCM3 data to assess the future climate change impact on water resources. The study indicated a likely future increase in runoff under A2 scenario, and a decrease in summer and autumn runoff under the B1 scenario. Contrary to the previous studies, no change to the average magnitude of spring peak flows under both scenarios is expected (Kim et al., 2008). Also, Choi et al. (2008) coupled SLURP model with downscaled A1B, A2 and B1 emission scenarios, generated from different GCMs (HadCM3 and CGCM3), in the Taylor and the Burntwood River basins in northern Manitoba, Canada. The results revealed inconsistencies in the projected precipitation; such changes are projected to lead to an overall increase in runoff, in particular, under the A1B emission scenario.

Kriaučiūnienė et al. (2009) combined HBV hydrological model with downscaled temperature and precipitation from two GCMs (ECHAM5 and HadCM3), using three emission scenarios (A1B, A2 and B1), in the Merkys river basin, Lithuania. Results indicated a decrease in the average annual runoff in comparison with the baseline period for the three scenarios. Similarly, Yu and Wang (2009) investigated the impact of climate change on rainfall, evapotranspiration, and discharge of the Shihmen reservoir in northern Taiwan. The monthly rainfall and temperature projection outputs from six GCMs under different climate change scenarios were used as inputs into a weather generator to produce a projection of daily rainfall and temperature series. The generated daily rainfall and temperature series were used with the calibrated HBV model to predict the impact of climate change on hydrological processes. The study showed an increase in rainfall and discharge during the wet season (May to October) and a decrease during the dry season (November to April of the following year), as well as an expected increase in the potential evapotranspiration patterns throughout the year except November and December.

Most impact studies using downscaled GCM data have focused on the impact of climate change on streamflow response. There has been limited work on the dynamics of soil moisture, evapotranspiration and other hydrological processes in response to projected change. However, it is change to these reservoirs and processes that will have a larger impact on terrestrial ecosystems.

5.5 Study areas

The GSDW (Keshta et al., 2009) model is used to simulate the hydrological performance of two reconstructed watersheds and one mature forest natural watershed under projected climate change scenarios. The reconstructed watershed study sites are located north of Fort McMurray, Alberta, Canada ($57^{\circ}39'N$ and $111^{\circ}13'W$). The first site is one of three experimental inclined sub-watersheds, entitled D3 cover, constructed in 1999 by the Syncrude Canada, Inc. The D3 soil cover has a slope of 5H:1V with an area of 1 ha and a thickness of 0.2 m of peat/mineral mix overlying 0.8 m of glacial till, respectively, overlying saline sodic shale (Keshta et al., 2009). The second study site was the South West Sand Storage (SWSS), constructed of 0.2-0.4 m of till/secondary cover material over 1.0 m of tailing sands (Keshta et al., 2009). Several experimental and modeling studies have been conducted regarding the hydrological performance of the two reconstructed watersheds, and have shed some light on the hydrological behaviour of those reconstructed watersheds (Boese, 2003; Shurniak, 2003; Elshorbagy et al., 2007, Elshorbagy and Barbour, 2007, Keshta et al., 2009). An extensive monitoring program has been carried out on both reconstructed watershed sites (since 1999 for D3; and since 2001 for SWSS) monitoring hourly meteorological variables of air temperature (AT), net radiation (NR), water vapour gradients, and soil temperature. Other soil-related variables (e.g., matric soil suction, and volumetric moisture content) are measured twice daily using time-domain reflectometry (TDR) and soil suction sensors at different depths. Measurements of the evapotranspiration were made with the eddy covariance technique (EC), and reported in 30-min intervals (Carey, 2008).

The third study site is an old aspen (OA) mature natural watershed, which was part of the former Boreal Atmosphere Exchange Study (BOREAS). The site (OA) is located near the south end of Prince Albert National Park, Saskatchewan, Canada (53.629° N, 106.198° W). The soil is a well drained loam to clay loam. The top 0.1 m layer is an organic layer (leaf litter, plus fermentation layer); underlain by a 0.07-0.3 m of till mixed with sand and clay, a 0.45 m layer derived from gravelly and clay enriched till, overlying a mixture of sandy clay loam of 0.40 m depth. The field instrumentation of the OA site has been providing continuous measurements since 1997 as part of the Boreal Ecosystem Research and Monitoring Sites (BERMS) program. Additional information on the OA site can be obtained from Cuenca et al. (1997). For the OA watershed, several studies have been carried out to estimate the water balance, soil temperature, and moisture conditions (e.g. Cuenca et al., 1997; Balland et al., 2006), and to use the site as a natural reference to assess the hydrological performance of reconstructed watersheds (Bachu and Elshorbagy, 2009; Keshta et al., 2009; Keshta et al., 2010).

5.6 Methodology

To achieve the study objectives, the following tasks will be completed: (1) downscaling GCM air temperature and precipitation using the 20th century baseline data along with the onsite data, and developing local climate scenarios, and (2) running the calibrated GSDW model with the downscaled A2 and B1 scenarios (2001-2100) to generate future long term soil moisture patterns, and thereby, producing frequency curves of the annual soil moisture deficit and evapotranspiration flux.

5.6.1 Statistical downscaling technique and climate scenarios

5.6.1.1 Coupled Global Climate Model (CGCM's) data

The third version of the Canadian Centre for Climate Modelling and Analysis (CCCma) Coupled Global Climate Model (CGCM3), was selected to provide the simulation data for a 20th century baseline period (20C3M, 1961-2000), and for the 21st century (2001-2100) based on A2 and B1 emission scenarios. The Coupled Global Climate Model (CGCM3) makes use of the same ocean component as that used in the earlier second generation Coupled Global Climate Model (CGCM2), but makes use of a substantially updated atmospheric component. The updated third generation, Atmospheric General Circulation Model (AGCM3), has a higher horizontal and vertical resolution than that used in AGCM2, as well as a new Canadian Land Surface Scheme (CLASS) for treating land surface processes (Verseghy et al., 1993). The A2 emission scenario, a high emission scenario, signifies less consciousness in terms of environmental, resources, and social interactions among regions, whereas, B1 emission scenario, a low emission scenario, represents a high level of environmental and social consciousness combined with a globally coherent approach to more sustainable development (IPCC, 2000). In general, all emission scenarios depict a society that is more affluent than today. Also, the utility of current GCMs is limited by the incomplete understanding of the climate system, as well as, the ability to transform this incomplete understanding into mathematical representations.

5.6.1.2 Statistical Downscaling Model (SDSM)

Due to the coarseness of the GCM output, it is necessary to construct statistical relationships between GCM outputs and local climate variables such as temperature and precipitation that can be used as input for regional and local hydrological models. The consensus of studies comparing dynamical and statistical downscaling methods is that both have comparable performance at estimating surface weather variables under the present climate conditions. The predictability of both methods of future climate change depends on the realism of the GCM outputs (Wilby et al., 2002). Statistical downscaling is simpler compared to the dynamical techniques, and can be repeatedly re-run to generate large ensembles of daily precipitation series at the point/catchment scale. In this study, the Statistical Downscaling Model (SDSM- Wilby et al. (2002)) was adopted.

The SDSM is largely based on regression models between GCM predictors and local variables (e.g., precipitation and air temperature) during the baseline period. In this study, the SDSM was calibrated using daily precipitation and air temperature data for the CGCM3 baseline period (20C3M, 1961-1990) and validated using CGCM3 data for (20C3M, 1991-2000). The downscaled CGCM3-20C3M (1991-2000) precipitation and temperature data during the validation period were compared to those of the local Environment Canada meteorological weather station at Fort McMurray, Alberta, Canada. The results showed that *temp* (mean temperature), *P850* (850 hPa geopotential height) and *s500* (specific humidity at 500 hPa height) are the most relevant predictors. The calibrated SDSM was then forced using the same predictor variables to produce future climate under A2 and B1, high and low emission scenarios, respectively. The projected

climate change under A2 and B1 emission scenarios were carried out for all sites using the downscaled GCM's data from the nearest grid to the reconstructed watersheds.

5.7 Hydrological modeling

The GSDW model (Keshta et al., 2009) was applied to simulate the soil moisture dynamics and evapotranspiration. The GSDW model is a lumped conceptual model designed to simulate the various components of watershed hydrology based on the surface energy and water balances in semi-arid regions. The GSDW model requires daily meteorological data, soil properties, and rudimentary site descriptors to simulate canopy interception, evapotranspiration, surface runoff, interflow, infiltration, and soil moisture redistribution in unsaturated/saturated layers. More details of the model formulations can be found in Keshta et al. (2009). The GSDW model was manually calibrated using soil moisture and evapotranspiration data for the designated watersheds based on local weather stations and eddy covariance tower data. Calibration was performed by setting individual parameter values and conducting a series of simulations, based on trial and error procedure, until no further improvement in the values of the error measures was achieved. The goodness-of-fit between the measured and simulated soil moisture and evapotranspiration values were quantified by using multiple performance indicators; the root mean squared error (RMSE), the mean absolute relative error (MARE), the correlation coefficient (R), and visual inspection of the observed and simulated variables. The GSDW model was previously used by Keshta et al. (2010) and Keshta and Elshorbagy (2010) to simulate long term soil moisture patterns for the three designated watersheds. The same previously calibrated models were used to estimate long term soil

moisture patterns and annual evapotranspiration for the downscaled projected A2 and B1 emission scenarios. The GSDW model was calibrated using the data from year 2003 and validated over the period of 2004-2006 for the D3 and the SWSS watersheds, whereas the OA-model was calibrated for 2000 and validated for 1999. Additional information about the calibration and validation procedures can be obtained from (Keshta et al. 2010; Keshta et al. 2009).

5.8 Long term probabilistic assessment of the hydrological performance of reconstructed watersheds

Downscaled CGCM3 data for the SRES A2 and B1 emission scenarios were used with the GSDW model to simulate soil moisture patterns based on the projected future climate change (2001-2100). Subsequently, a probabilistic framework, initially developed by Elshorbagy and Barbour (2007), was adopted to obtain frequency curves of the maximum annual soil moisture deficit values. Based on the obtained frequency curves, the probability that the reconstructed watersheds could provide the desired threshold of moisture demand was assessed. The long term simulations were carried out for all sites using the downscaled GCM data from the nearest grid to the reconstructed watersheds, which allowed for comparing the hydrological performance of the reconstructed systems with the undisturbed natural systems based on a common climatic basis and fully developed vegetation.

The calibrated models were executed for 100 years using the downscaled precipitation and air temperature data from the GCM to obtain daily soil moisture values.

The daily soil moisture values within the root zone were summed during the growing season, and the difference in soil moisture content (ΔS) between the current day (S_t) and the immediate subsequent day (S_{t+1}) was computed. The difference between ΔS and the sum of the interflow and percolation below the root zone is the daily moisture deficit (D_t). A positive value of D_t indicates the depletion of soil moisture (moisture deficit) due to evapotranspiration, and represents the amount of water the soil cover stored and released for vegetation in one day. Daily D_t values over the growing season were accumulated, and the maximum obtained cumulative D_t value is called the maximum annual soil moisture deficit (D_m). A positive value of D_m represents the maximum amount of moisture stored and released for vegetation in one year (Elshorbagy and Barbour, 2007). A probability distribution was fitted based on the D_m (100 values), and the best fit distributions were selected for each watershed based on their Chi-squared goodness of fit. The same probabilistic framework was adopted to obtain the annual actual evapotranspiration (AET) flux frequency curves. The obtained frequency curves were compared against those obtained using a 50-year dataset extracted from the onsite Environment Canada historical records, providing assessment of the hydrological performance of the watersheds due to the projected climate change impact in the 21st century.

5.9 Results and Discussion

5.9.1 Downscaling results during the baseline period

The average annual precipitation value recorded by Environment Canada's meteorological station at Fort McMurray during the baseline period is 454 mm, while the SDSM predicted an average annual value of 470 mm during the validation period (1991-2000). Kendall's non-parametric test was conducted on the baseline statistically downscaled daily precipitation and the local precipitation daily time series. Analysis showed a Kendall's coefficient of concordance, used for assessing agreement, where 0 signifies no agreement and 1 signifies complete agreement, of 0.027, indicating statistically significant differences between the two precipitation series. Downscaled temperature data were close to local temperature daily time series. Maximum daily temperature was 27.2 °C for the downscaled temperature compared to 26.7 °C for the instrumental record, and a downscaled minimum daily temperature of -43.4 °C compared to a value of -41.1 °C during the validation period. The R-statistics between local daily temperature series and statistically downscaled temperature was 0.77.

5.9.2 Downscaled GCM outputs corresponding to future climate scenarios

Distributions of the percentiles for daily precipitation (mm/day) and temperature from the Fort McMurray station and the A2- and B1-downscaled emission scenarios were compared (Table 5-1). The median (50th percentile) precipitation values for the evaluation period at the Fort McMurray station and B1 emission scenario were zero, meaning that more than 50% of the days experienced no precipitation. The 99th percentile

was higher for the station data, suggesting that A2 and B1 emission scenarios underestimated the frequency of extreme precipitation events, while the descriptive statistical analysis (Table 5-2) indicated that A2- and B1-downscaled emission scenarios overestimated the cumulative annual precipitation. The A2 and B1 emission scenarios temperature values have positive distributions shifts relative to the station-recorded temperature, suggesting a warm bias in summer of around 4.3 and 1.6 °C (99th percentile), respectively. During the winter period, A2 scenario tended to be warmer relative to the station-recorded temperature of around 6.5 and 4.6 °C (5th and 25th percentiles), while B1 scenario tended to be colder relative to the station recorded temperature of around 3.4, 1.0, and 3.7 °C at 5th, 25th and 50th percentiles, respectively.

Table 5-1 Percentiles of daily precipitation (mm/day) and temperature (°C) at Fort McMurray station and SDSM-downscaled CGCM3 scenarios.

Year	Source	Percentile					
		5th	25th	50th	75th	95th	99th
Precip.	Station	0.0	0.0	0.0	0.8	6.6	17.8
	A2	0.0	0.0	0.7	2.0	6.6	14.9
	B1	0.0	0.0	0.0	1.6	5.8	13.2
Temp.	Station	-27.0	-9.9	3.4	12.6	18.9	21.8
	A2	-20.5	-5.3	3.9	13.9	22.4	26.1
	B1	-30.4	-10.9	-0.3	8.2	17.8	23.4

Table 5-2 summarizes the annual average values of precipitation during the baseline period (1961-2000), and A2- and B1-downscaled emission scenarios for (2001-2100). The Fort McMurray station has an average annual precipitation value of 454 mm during the baseline period, while SDSM predicted an increase of 34% and 8.6% for A2 and B1 emission scenarios, respectively. The Kendall's non parametric test was conducted on multiple related samples. The analysis showed a Kendall's coefficient of concordance of 0.032 for the three precipitation datasets, a Chi-squared value of 923 with two degrees of freedom, and a p-value of zero. This shows a significant difference in means and variance, and reflects statistically significant differences among the three precipitation series.

Table 5-2 Descriptive statistical properties of precipitation (mm/day) and temperature (°C) at Fort McMurray station and SDSM-downscaled scenarios.

Statistics	Precipitation			Air temperature		
	Station	A2	B1	Station	A2	B1
SD ^a	3.7	3.5	3.1	14.4	13.1	14.4
Average	454.1	607.0	493.1	0.5	3.30	2.4
Maximum	95.0	115.5	78.3	26.7	33.3	25.9
Minimum	0.0	0.0	0.0	-41.1	-39.0	-44.4

^a standard deviation

The average temperature for Fort McMurray are 3.3 and 2.4 °C with A2 and B1 emission scenarios, respectively, compared with 0.5 °C for the baseline Fort McMurray data.

5.9.3 Long term probabilistic assessment of moisture deficit

The calibrated GSDW model was used along with the downscaled A2 and B1 emission scenarios (2001-2100) to evaluate the current/future hydrological performance of the study areas with respect to soil moisture deficit using the probabilistic framework described in section 4. The results were compared with the long term performance estimates using the onsite Environment Canada (EC) historical dataset. For both emission scenarios and EC datasets, the normal (μ , σ) distribution was found to fit the datasets of the D3 cover (Figure 5-1), where μ and σ are the mean and the standard deviation of the distribution. D_m values for A2 and B1 emission scenarios were negatively shifted, indicating surplus water due to the projected increase in precipitation in the 21st century compared to the EC- D_m values. According to the EC and GCM datasets, the D3 cover at the 90% non-exceedance probability is able to store and release up to 134, 87 and 104 mm of moisture for EC, A2, and B1 emission scenarios, respectively. At a non-exceedance probability of 90%, this soil cover would be required, on average, to store-and-release this amount of moisture ten times in 100 years. For the D3 cover, the D_m distributions were determined to be:

D3-EC; Normal(79.5, 42.7)

D3-A2 SRES; Normal(40.8, 35.8)

D3-B1SRES; Normal(54.2, 38.9)

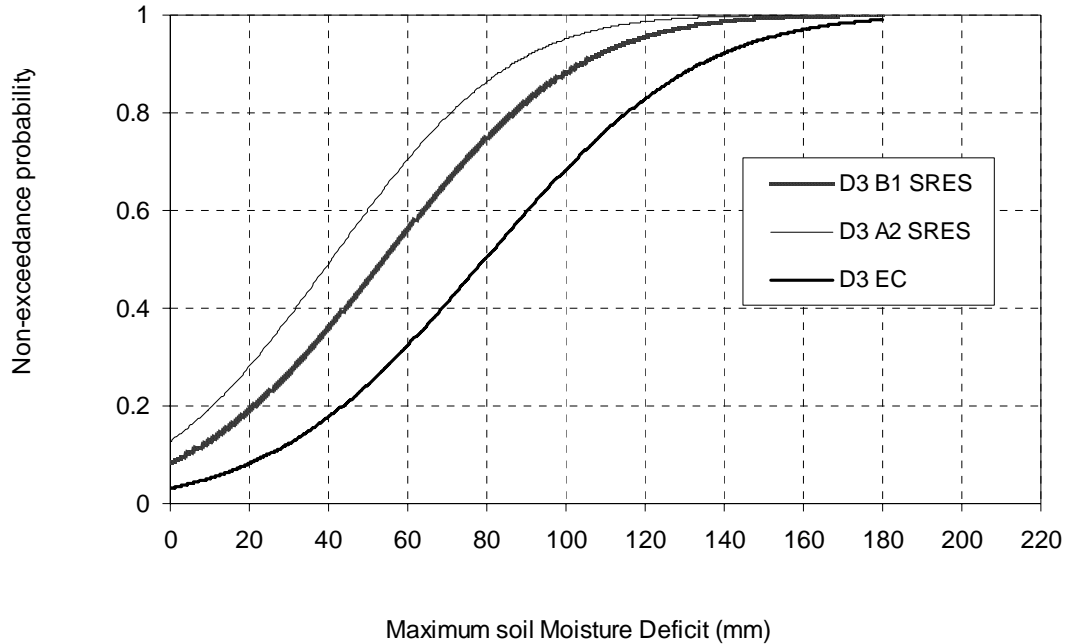


Figure 5-1 Probabilistic comparison of the hydrological performance of the D3 cover based on EC dataset and CGCM3 scenarios.

The best distribution for the SWSS watershed was found to be normal (μ , σ) based on EC dataset, while the best fitted distribution for both A2 and B1 emission scenarios was found to be Logistic (α , β), where α and β are the continuous location and shape parameters. The SWSS-A2 D_m (Figure 5-2) exhibits a tendency to store and release less moisture ($\geq 50\%$ non-exceedance probability) compared to the SWSS-EC maximum moisture deficit. The SWSS watershed showed the ability to store and release up to 117, 90, and 114 mm of moisture at the 90% non-exceedance probability using EC, A2, and B1 emission scenarios, respectively. For the SWSS watershed, the D_m distributions were:

SWSS-EC site; Normal(61.2, 43.2)

SWSS-A2 SRES; Logistic(63.7, 23.0)

SWSS-B1 SRES; Logistic(61.0, 13.3)

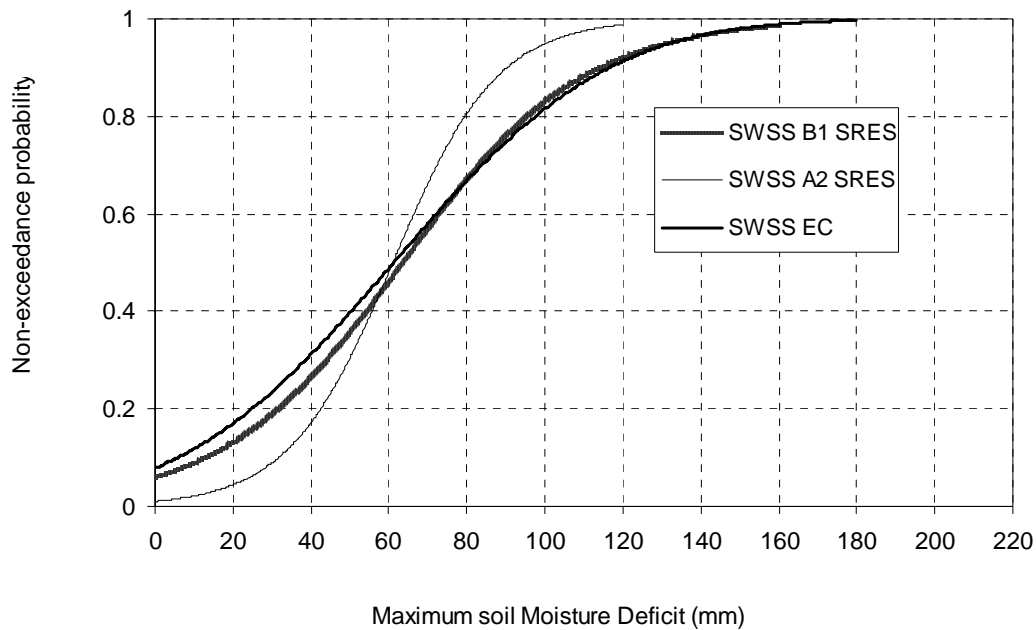


Figure 5-2 Probabilistic comparison of the hydrological performance of the SWSS watershed based on EC dataset and CGCM3 scenarios.

Generally, the SWSS soil cover needed to store and release more moisture under both emission scenarios compared to the D3 cover. The dichotomy in the behaviour of the two soil covers is illustrated in Figures 5-1 and 5-2, which indicates good draining ability of the SWSS sandy soil texture. In contrast, the volume of stored moisture in the D3 soil cover, comprised mainly of glacial till over saline sodic shale, retained moisture for longer periods due to its lower hydraulic conductivity. Moreover, impermeable or near impermeable layers at D3 may cause the formation of perched water table on top of them, thereby reducing moisture deficit values. Similar results were interpreted in Barros et al. (1999), who showed that higher hydraulic conductivity in sandy soils is associated with higher infiltration rates, and thus, higher moisture deficit values.

For the OA watershed, the best distribution was found to be Weibull (α , β), where α is the shape parameter and β is scale parameter, based on EC dataset, while the best fitted distributions based on the A2 and the B1 emission scenarios were found to be Logistic (α , β) and BetaGeneral (α_1 , α_2 , min, max), respectively (Figure 5-3). The D_m values show a tendency to store and release less moisture at $\geq 45\%$, as well as at $\geq 65\%$ non-exceedance probabilities for OA-A2, and OA-B1, respectively, compared to the OA-EC. The OA watershed showed the ability to store and release up to 130, 95, and 109 mm of moisture at the 90% non-exceedance probability using EC, A2, and B1 emission scenarios, respectively. For the OA watershed, the D_m distributions were determined to be:

OA-EC; Weibull(2.2080, 96.325) Shift=-10.373

OA-A2 SRES; Logistic(68.386, 11.855)

OA-B1 SRES; BetaGeneral(17.322, 4.9688, -173.71, 147.10)

The probabilistic comparisons for the three sites indicate a decrease in the projected soil moisture deficit based on A2 and B1 emission scenarios due to the expected increase in precipitation rates. In general, the inconsistency of timing, location, and intensity of the precipitation events among the three datasets and the soil stratifications affect the moisture dynamic patterns in the soil, which in turn affect the daily soil moisture deficit in value and trend. The pre-analysis of the three datasets indicated a tendency for the A2 and B1 to underestimate the peak values of precipitation compared to the EC dataset, while both scenarios tend to overestimate the cumulative annual precipitation.

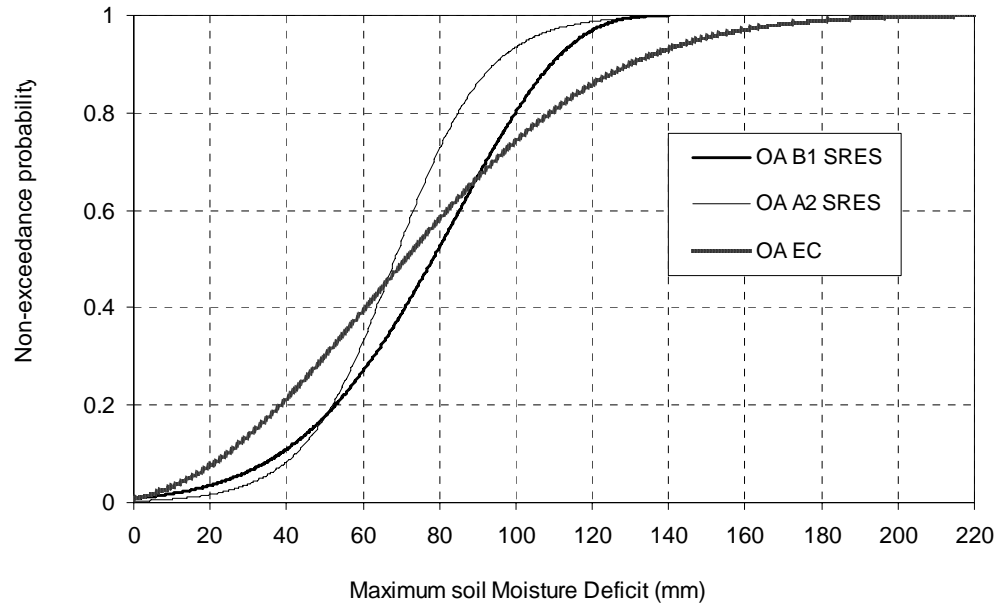


Figure 5-3 Probabilistic comparison of the hydrological performance of the OA watershed based on EC dataset and CGCM3 scenarios.

The results of this study show a sizeable impact of projected climate change on the hydrologic regimes in the study areas. Under the same precipitation event, soil texture stratification may strongly impact soil moisture patterns, leading to significant decrease/increase in moisture deficit patterns. Results suggested that the D3 cover needs to store and release less moisture under future climate scenarios compared to the other two sites. The D3 cover is comprised of an upper peat layer with high hydraulic conductivity that rapidly transfers soil moisture to the lower till layer, thereby reducing evapotranspiration. The saline sodic shale layer at depth, having limited hydraulic conductivity, reduces moisture depletion from the till layer by reducing percolation and reducing the variance in moisture deficit values. This finding emphasizes the role of soil stratification in reclaimed sites to maintain high degree of saturation. The same finding was interpreted in Yanful et al. (2003), who showed that evaporation from clayey till could be curtailed by placing a higher conductivity-textured soil above the till. The

SWSS site is dominated by sandy texture soil that drains rapidly, resulting in increased moisture deficit values. The OA site is comprised of coarse textured soil as a top layer overlying a gravely and clay enriched till with lower hydraulic conductivity than the top layer. This suggests that the lower layer could retain moisture as the coarser layer on top enhances percolation, thereby increasing the degree of saturation and reducing moisture deficit values. Similar finding was reported by Yanful et al. (2003).

5.9.4 Hydrological performance assessment based on actual evapotranspiration

(AET) fluxes

Hydrological processes, such as soil moisture redistribution and evapotranspiration, are intrinsically linked. Under warmer future conditions, the increase in precipitation patterns is correlated to increases of evapotranspiration. Thus, the actual evapotranspiration (AET) fluxes frequency curves were constructed to identify the ability of each watershed to release water for evapotranspiration. The simulated daily AET values were summed for each growing season and the total annual values were treated as a random variable to fit probability distribution curves. Figure 5-4 shows the fitted annual AET distributions during the growing season. At 90% non-exceedance probability, transpiration at the D3 cover was 323, 336, and 397 mm based on EC, B1 and A2 emission scenarios, respectively. The details of the AET probability distributions are presented below:

D3-EC; Normal(271.7, 39.9)

D3-A2 SRES; BetaGeneral(5.70, 4.34, 218.39, 453.39)

D3-B1 SRES; InvGauss(162.27, 2681.77) Shift=+120.97

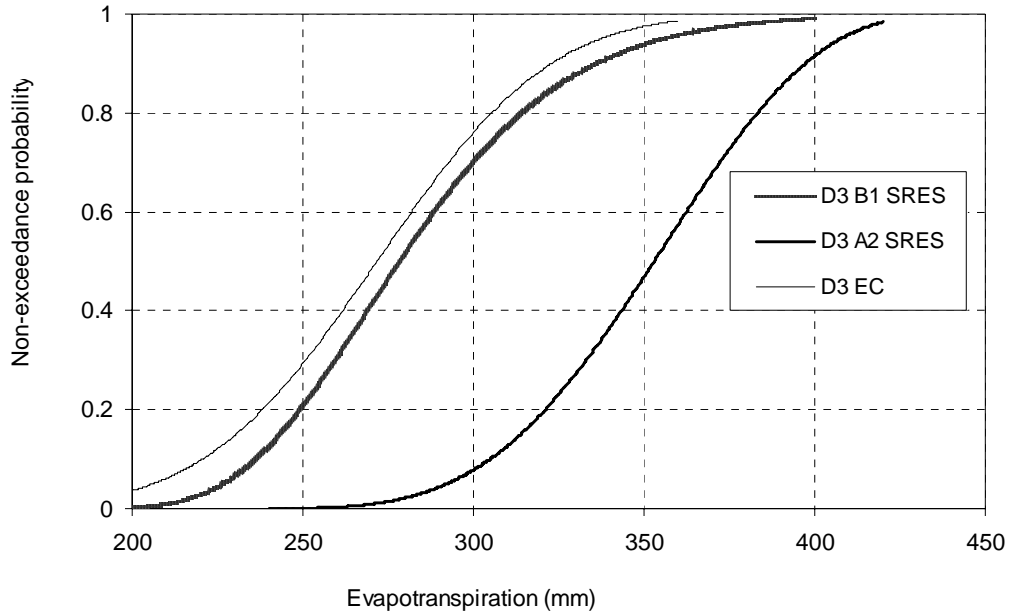


Figure 5-4 Frequency curve of growing season evapotranspiration fluxes for D3 cover.

Figure 5-5 shows the fitted distributions of the annual growing season AET fluxes for the SWSS site. At 90% non-exceedance probability, transpiration at the SWSS site was 330, 356, and 456 mm based on EC, B1, and A2 emission scenarios, respectively. The details of the AET probability distributions are presented below:

SWSS-EC site; Weibull(2.4, 97.7) Shift=+192.8

SWSS-A2 SRES; Weibull(6.19, 407.39) Shift=-9.91

SWSS-B1 SRES; Logistic(303.76, 24.11)

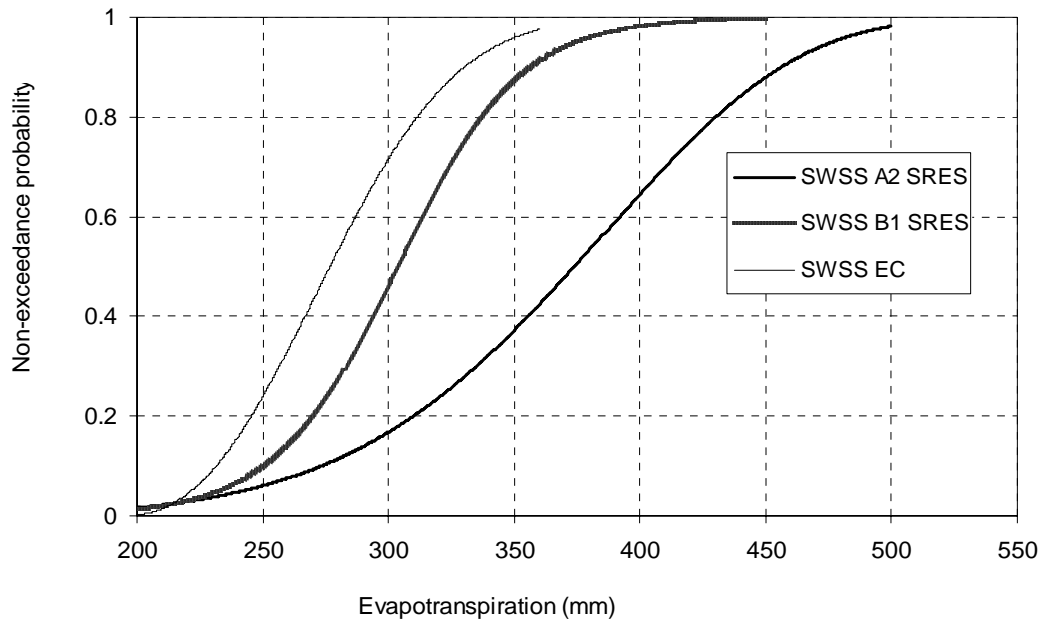


Figure 5-5 Frequency curve of growing season evapotranspiration fluxes for SWSS site. Similarly, Figure 5-6 shows the fitted distributions of the annual growing season

AET fluxes for the natural old Aspen (OA) site. At 90% non-exceedance probability, evapotranspiration at the OA watershed was 411, 520 and 662 mm based on EC, B1 and A2 emission scenarios, respectively. The greater value and increase in AET at OA compared with the reconstructed watersheds is attributed to the mature aspen vegetation, which evaporates at values greater than the immature vegetation at the reclamation sites. It should be noted that the reconstructed watersheds are evaluated based on the current vegetation conditions. The dynamic vegetation growth is not included in the GSDW model. The details of the AET probability distributions are:

OA-EC; Weibull(1.54, 122.56) Shift=+200.10

OA-A2 SRES; Normal(533.23, 100.67)

OA-B1 SRES; Weibull(2.87, 214.24) Shift=+233.79

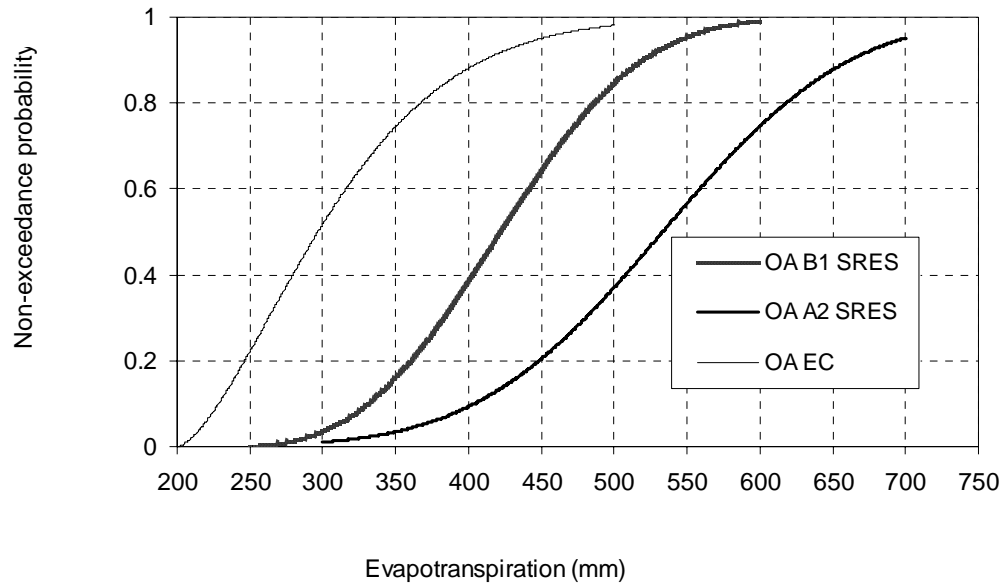


Figure 5-6 Frequency curve of growing season evapotranspiration fluxes for OA watershed.

Overall, the results imply that watersheds will experience an increase in the actual evapotranspiration under future climate change scenarios. The A2 emission scenario allows for more evapotranspiration than the historical EC and the B1 emission scenario, while the OA watershed has greater evapotranspiration compared to the reconstructed watersheds, largely due to the mature vegetation at this site. Results show that the D3 cover AET flux values were less than the SWSS and the OA AET values. The top layer, with higher hydraulic conductivity, compared to the subsequent layer, comprised of enriched glacial till, with inferior hydraulic conductivity is working to speed infiltration rates, thereby reduce AET values from the top layer compared to the other study areas. These results should be treated with caution for several reasons: first, because of the GSDW model uncertainty; second because the canopy future transformation can alter the land-atmosphere interaction (Entekhabi et al., 1996), and

third, the uncertainties associated with the GCM data outputs and with the downscaling techniques.

5.10 Conclusions

This study has sought to develop a generalized understanding of the sensitivity of long term soil moisture patterns to changes in the projected precipitation in the 21st century. The projections of climate change impacts on soil moisture patterns were simulated based on the CGCM3 and two emission scenarios for greenhouse gases (A2, B1). The SDSM was used, for transferring the climate change signal to onsite regional scale, along with a calibrated hydrological model entitled GSDW. Information from both statistically downscaled CGCM3 scenarios indicated an increase in the mean annual temperature for Fort McMurray of 3.3 and 2.35 °C, and an increase in the predicted annual precipitation of 34% and 8.6% with A2 and B1 emission scenarios, respectively. The patterns of changes in precipitation intensity in a warmer future will most likely lead to an increase in evapotranspiration combined with lengthening of the growing season.

Inter-comparison and validation of the future performance of reconstructed watersheds based on the obtained climate information from both statistically downscaled GCM outputs and from past climate analogues (EC historical records) showed a tendency to store and release more moisture under high demands using the EC than A2 and B1 emission scenarios. This variance is due to precipitation discrepancies between both datasets in peaks, timing, and intensity of single events. Under warmer future, evidence suggests that the need for water storage capacity in the three watersheds might not

increase considerably, due largely to the expected increase in precipitation rates. The forecasted maximum moisture deficit is expected to slightly decrease due to precipitation surplus, while evapotranspiration in the study areas are expected to increase. It is interesting to note that the impacts of climate change, based on the A2 and B1 scenarios, are not expected to increase the risk of failure of the studied reconstructed watersheds; i.e., the changes will not adversely affect the ability of the reconstructed watersheds to store-and-release water for vegetation.

In conclusion, studying the projected impact of precipitation change in future combined with the probabilistic approach to evaluate the maximum soil moisture deficit should contribute to improving our knowledge about regional response to climate change. The methodology discussed in this paper may provide means for better management of existing/newly reconstructed watersheds under the projected climate change. Soil properties (e.g., porosity, water holding capacity, and hydraulic conductivity) vary significantly with time due to vegetation growth. In this study, the canopy was assumed to be static, missing the dynamic effect of vegetation due to the growth, pinpointing the need to connect this type of study to other models that simulates long term vegetation dynamics.

5.11 Acknowledgements

The authors acknowledge the financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC), the Cumulative Environmental

Management Association (CEMA), and the Department of Civil and Geological Engineering, University of Saskatchewan, Canada.

5.12 References

Bachu, L., and A. Elshorbagy, 2009. Hydrology of reconstructed and natural watersheds.

Modeling based comparative analysis of hydrological performance. VDM Verlag Dr. Muller Aktiengesellschaft & Co., Saarbrücken, Germany.

Balland, V., J. Bhatti, R. Errington, M. Castonguay, and P.A. ARP, 2006. Modeling snowpack and soil temperature and moisture conditions in a jack pine, black spruce and aspen forest stand in central Saskatchewan (BOREAS SSA). *Canadian Journal of Soil Science*, 86:203-217.

Barros, A.P., D. Knapton, M.C. Wang and C.Y. Kuo, 1999. Runoff in shallow soils under laboratory conditions. *Journal of Hydrologic Engineering*, 4(1):28-37.

Bergstrom S, Carlsson B, Gardelin M, Lindstrom G, Pettersson A, Rummukainen M. 2001. Climate change impacts on runoff in Sweden assessments by global climate models, dynamical downscaling and hydrological modelling. *Climate Research*, 16(2): 101–112.

Boese, K., 2003. The design and installation of a field instrumentation program for the evaluation of soil-atmosphere water fluxes in a vegetated cover over saline/sodic shale overburden, *MSc Thesis, University of Saskatchewan, Saskatoon, Saskatchewan, Canada*, 169 pp.

- Canadian Association of Petroleum Producers (CAPP), 2008a. Environmental challenges and progress in Canada's oil sands. April, 2008. <http://www.capp.ca/getdoc.aspx?DocID=135721>.
- Canadian Association of Petroleum Producers (CAPP), 2008b. Oil sands & western Canadian conventional production, December 2008 interim update. December, 2008. <http://www.capp.ca/>.
- Carey, S.K., 2008. Growing season energy and water exchange from an oil sands overburden reclamation soil cover, Fort McMurray, Alberta, Canada, *Hydrological Processes*, 22:2847–2857.
- Choi, W., A. Moore, K. Koenig, and P.F. Rasmussen, 2008. Response of hydrological systems to statistically downscaled GCM output in the northern Manitoba (Canada) boreal forest region. *Proceedings for the 13th World Water Congress*, Montpellier, France, 13 pages, 1-4 September 2008
- Cuenca, R.H., D.E. Stangel, and S.F. Kelly, 1997. Soil water balance in a boreal forest. *Journal of Geophysical Research*, 102(D24):29,355-29,365.
- Cunderlink, J. and Simonovic, S. (2005): Hydrological extremes in a southwestern Ontario river basin under future climate conditions; *Hydrological Sciences Journal*, 50(4):631–654.
- Elshorbagy A., A. Jutla, and J. Kells, 2007. Simulation of the hydrological processes on reconstructed watersheds using system dynamics, *Hydrological Science Journal*, 52(3):538–561.

- Elshorbagy, A. and S.L. Barbour, 2007. A probabilistic approach for design and hydrologic performance assessment of reconstructed watersheds, *Journal of Geotechnical & Geoenvironmental Engineering ASCE*. 133(9):1110–1118.
- Elshorbagy, A., A. Julta, L. Barbour and J. Kells, 2005. System dynamics approach to assess the sustainability of reclamation of distributed watersheds, *Canadian Journal of Civil Engineering*, 32:144–158.
- Entekhabi D., Rodriguez-Iturbe I., and Castelli F. 1996. Mutual interaction of soil moisture state and atmospheric processes. *Journal of Hydrology* 184:3-17.
- Gebremeskel S., Liu Y.B., Smedt F.D., Hoffmann L. and Pfister L., 2005. Analysing the effect of climate changes on streamflow using statistically downscaled GCM scenarios. *International Journal of River Basin Management*, 2(4):271–280
- Gilley, J.E., G.W. Gee, A. Bauer, W.O. Willis and R.A. Young, 1977. Runoff and erosion characteristics of surface mined sites in western North Dakota, *Transactions of American Society of Agricultural Engineers*, 20(4):697–704.
- Groisman, P. Ya., R. W. Knight, D. R. Easterling, T. R. Karl, G. C. Hegerl, and V. N. Razuvaev, 2005: Trends in intense precipitation in the climate record. *Journal of Climate*, 18, 1326–1350.
- IPCC (Intergovernmental Panel on Climate Change), 2000. Land Use, Land-Use Change and Forestry. R.T. Watson, I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo, and D.J. Dokken (eds.). Cambridge University Press, Cambridge, U.K.
- IPCC, 2007. Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon et al., Cambridge Univ. Press, New York.

- Julta, A.S., 2006. Hydrologic modeling of reconstructed watersheds using a system dynamics approach, *M.Sc. Thesis, University of Saskatchewan, Canada*, 139 pp.
- Keshta, N., A. Elshorbagy and S. Carey, 2009. A generic system dynamics model for simulating and evaluating the hydrological performance of reconstructed watersheds, *Hydrology and Earth System Sciences*, 13(6):865–881.
- Keshta, N., A. Elshorbagy, and L. Barbour, 2010. Comparative probabilistic assessment of the hydrological performance of reconstructed and natural watersheds. *Hydrological Processes*, DOI: 10.1002/hyp.7596.
- Keshta, N., and A. Elshorbagy, 2010. Utilizing North American Regional Reanalysis for modeling soil moisture and evapotranspiration in reconstructed watersheds. *Physics and Chemistry of the Earth Journal* (Revised manuscript submitted in October 2010: JPCE-D-09-00231R1).
- Kharin, V.V., and F.W. Zwiers, 2000: Changes in the extremes in an ensemble of transient climate simulations with a coupled atmosphere–ocean GCM. *Journal of Climate*, 13:3760–3788.
- Kilkus K., A. Štaras, E. Rimkus, and G. Valiuškevičius, 2006. Changes in water balance structure of Lithuanian rivers under different climate change scenarios. *Environmental research, engineering and management*, 2(36):P.3-10.
- Kim, S.J., M. Lee, W. Choi, and P.F. Rasmussen, 2008. Utilizing North American Regional Reanalysis for climate change impact assessment on water resources in central Canada. Proceedings for the 13th World Water Congress, Montpellier, France, 14 pages, 1-4 September 2008 (TCO: 1)

- Kriaučiūnienė J., D. Šarauskienė and B. Gailiusis, 2009. Estimation of uncertainty in catchment-scale modeling of climate change impact (case of the Merkys River, Lithuania). *Environmental Research, Engineering and Management*. 1(47):P. 30-39.
- Meehl, G. A., J. M. Arblaster, and C. Tebaldi, 2005: Understanding future patterns of increased precipitation intensity in climate model simulations. *Geophysical Research Letters*, 32, L18719, doi:10.1029/2005GL023680.
- Menzel L, Burger G. 2002. Climate change scenarios and runoff response in the Mulde catchment (southern Elbe, Germany). *Journal of Hydrology*. 267:53–64.
- Merritt W.S., Y. Alila, M. Barton, B. Taylor, S. Cohen, and D. Neilsen, 2006. Hydrologic response to scenarios of climate change in sub-watersheds of the Okanagan basin, British Columbia. *Journal of Hydrology*, 326:79–108.
- Shongwe M.E., G.J. van Oldenborgh, B.J.J.M. van Den, B. De Boer Hurk, C.A.S. Coelho, and M.K. van Aalst, 2009. Projected changes in mean and extreme precipitation in africa under global warming. Part I: Southern Africa. *Journal of Climate*, 22:3819–3837.
- Shurniak, R.E., 2003. Predictive Modeling of Moisture Movement within Soil Cover Systems for Saline/sodic overburden Piles. *M.Sc. Thesis*, University of Saskatchewan, Canada.
- Ghosh, S. and P.P. Mujumdar, 2006. Future rainfall scenario over Orissa with GCM projections by statistical downscaling. *Current Science*, 90:(3)396-404.

- van Ulden, A.P., and G.J. van Oldenborgh, 2006: Large-scale atmospheric circulation biases and changes in global climate model simulations and their importance for climate change in Central Europe. *Atmospheric Chemistry and Physics discussions*, 6:863–881.
- Verseghy, D.L., N.A. McFarlane, and M. Lazare, 1993. A Canadian Land Surface Scheme for GCMs:II. Vegetation model and coupled runs. *Int. J. Climatol.*, 13:347-370.
- Wigley, T.W.L., Jones, P.D., Briffa, K. R. and Smith, G.: 1990. Obtaining sub-grid scale information from coarse resolution general circulation model output. *Journal of Geophys. Res.*, 95:1943–1953.
- Wilby, R.L. and Wigley, T.M.L.: 1997. Downscaling general circulation model output: a review of methods and limitations. *Progress in Physical Geography*, 21:530–548.
- Wilby, R.L., Dawson, C.W. and Barrow, E.M. (2002) SDSM - a decision support tool for the assessment of regional climate change impacts. *Environmental Modelling & Software*, 17:147-159.
- Yanful, E.K., S.M. Mousavi and M. Yang, 2003. Modeling and measurement of evaporation in moisture-retaining soil covers. *Advances in Environmental Research*, 7:783-801.
- Yonas, B.D. and Coulibaly P., 2007. Validation of hydrological models for climate scenario simulation: the case of Saguenay watershed in Quebec. *Hydrological Processes*, 21:3123–3135.
- Yu, P. and Wang, Y., 2009. Impact of climate change on hydrological processes over a basin scale in northern Taiwan. *Hydrological Processes*, 23:3556–3568.

Chapter 6 - Conclusions

6.1 Summary of the Thesis

In general, this thesis is comprised of two parts. The first part, which covers Chapters 2 and 3, is motivated by the idea of extending the usefulness of an in-house site-specific watershed system dynamics (SDW) model by developing a generalized system dynamics watershed (GSDW) model. Chapter 3 identifies and uses a probabilistic approach that can be adopted to assess the hydrological performance of reconstructed watersheds using maximum annual soil moisture deficit and actual evapotranspiration flux as indicators. The second part of the thesis, which includes Chapters 4 and 5, extends the use of the GSDW model (Chapter 2) and the probabilistic approach (Chapter 3) to watersheds with limited data and to the study of the impacts of possible climate change on the reclamation strategies.

In Chapter 2, the GSDW model was proposed and developed. The performance of the GSDW model was evaluated by applying it to two hydrological processes, namely (i) soil moisture redistribution modeling and (ii) actual evapotranspiration modeling in natural and reconstructed watersheds. The study demonstrated the suitability of the GSDW model compared to the earlier site-specific SDW model, which can be attributed to the modifications incorporated into the model structure. The performance of the GSDW model was compared with the Soil and Water Assessment Tool (SWAT) model that is widely adopted in hydrological and agricultural applications. The GSDW model and SWAT preliminary runs performed comparably. The aim of comparing both models

was to supply the modeller with an indication of which model to use based on a lumped dataset. The use of complex physically-based models, such as SWAT with lumped inputs, is neither effective nor economical. The GSDW model was shown to have a simpler structure with fewer calibrated parameters, and more reliance on widely available meteorological data. The study reported in Chapter 2 is a step towards developing a generic model rather than multiple site-specific models for simulating the hydrological processes in watersheds reconstructed using different reclamation strategies. This chapter provides a vital tool that will enable investigation of the utility of different soil cover alternatives and the evaluation of their performance.

Chapter 3 naturally stemmed from earlier work by Elshorbagy and Barbour (2007). The target of reconstructed covers is to have sufficient available water holding capacity (AWHC) to supply enough moisture over the growing season, thereby promoting vegetation growth. The risk of failure of proposed reclaimed (reconstructed) sites under various climatic scenarios is evaluated using frequency curves for maximum annual moisture deficit (D_m), creating a better representation of the AWHC concept. In this chapter, the work was extended to other sites (reconstructed and natural) and to other hydrological processes and applications. The idea was founded on the hypothesis that the robustness of the adopted probabilistic approach could improve our knowledge of the soil-atmospheric-vegetation interaction. The hypothesis was tested by using the GSDW model to simulate the long-term dynamics of soil moisture patterns and actual evapotranspiration fluxes in several watersheds with different topographic, soil, and vegetation conditions. The soil moisture values of all layers within the root zone were

summed to get the daily soil moisture series of each soil cover, and the difference in soil moisture content (ΔS) between the current day and the immediate subsequent day was computed. Accordingly, the daily moisture deficit (D_t) was computed as the difference between ΔS and the sum of the interflow and percolation below the cover. Daily D_t values over the growing season were summed to obtain D_m . The annual D_m and annual AET values (50 values representing 50 years) were treated as random variables and probability distributions were derived and fitted to both values for each soil cover. Accordingly, frequency curves of the D_m values were constructed and used to assess the probability of various reconstructed and natural watersheds being able to provide the associated moisture demands during the growing seasons. Results from the study showed a tendency for the reconstructed watersheds to provide less moisture for evapotranspiration than the natural forested systems. By adopting and applying the probabilistic approach, the knowledge gained was constructive for developing suggestions for new soil cover alternatives. The probabilistic framework was found useful for integrating the canopy of mature natural systems and transferring the results to the reconstructed systems. The results showed that the mature vegetation influenced the moisture deficit regime positively, signifying a greater possibility that reconstructed covers will adapt to the vegetation type and growth. The study reported in Chapter 3 is another step towards better understanding of reconstructed systems via the simulation of multiple scenarios using different soil/vegetation alternatives.

Chapter 4 demonstrated the reliability of using North American Regional Reanalysis (NARR) data for simulating the soil moisture dynamics compared to the use

of conventional platform data (e.g., metrological weather station data). For estimating the soil moisture patterns at two distinct reconstructed watersheds, two different versions of the GSDW model were generated based on the source of the weather data for calibration and validation purposes. The two versions of the GSDW model were applied, one calibrated using input data from the onsite weather station (SS-calibrated) and the other using precipitation and air temperature values from the NARR datasets with the remaining data obtained from the onsite weather station (NARR-calibrated). Both models were developed and tested with the objective of identifying the relative merits and demerits of adopting NARR data in hydrological modeling. In general, the NARR-calibrated model performance was shown to be reliable compared to the SS-calibrated model. The same probabilistic approach implemented in Chapter 3 was used along with the NARR long-term dataset (1979-2006) to evaluate the current/future hydrological performance of existing reconstructed watersheds with respect to soil moisture deficit. The results were compared to the findings of the previous chapter. Bearing in mind the discrepancies in the NARR dataset compared to the onsite weather station, the findings from this study reiterate that the NARR data can be exploited to simulate soil moisture patterns and may substantially assist with overcoming the challenges presented by the scarcity of weather stations (ungauged watersheds). However, data from onsite meteorological stations are essential to validate the NARR datasets.

It has been widely acknowledged in the literature that the projected change in future precipitation and air temperature patterns will affect runoff patterns, but limited literature evaluates the impact of future climate change on soil moisture patterns. Chapter

5 aimed to develop a generalized understanding of the sensitivity of soil moisture patterns to changes in the projected precipitation in the 21st century. The GSDW model was applied to three watersheds using climate scenarios. These scenarios were generated with statistically downscaled daily precipitation and air temperature outputs from a global climate model (CGCM3), under A2 and B1 emission scenarios, to simulate the corresponding soil moisture and actual evapotranspiration. The study indicates an increase in the mean annual temperature for the Fort McMurray area of 3.3 and 2.35°C, and an increase in the predicted annual precipitation of 34 and 8.6%, for A2 and B1 emission scenarios, respectively. Consequently, the GSDW model along with the Environment Canada historical baseline data and downscaled A2 and B1 emission scenarios were used to calculate the maximum annual soil moisture deficit of the designated watersheds. Bearing in mind the uncertainty associated with the downscaled A2 and B1 emission scenarios, the pattern of changes in the precipitation intensity in a warmer future are expected to lead to an increase in evapotranspiration combined with a lengthening of the growing season. Increased evapotranspiration implies more moisture in the air, thus producing a change in magnitude, intensity, and timing of any given precipitation event.

In summary, the use of the developed GSDW model and the application of the probabilistic approach in this thesis are not claimed to be exhaustive and hence may not address all pertinent issues with regard to the objectives of the study. Nevertheless, this study serves as a step forward in pursuit of attaining a sustainable reclamation protocol for the oil sands industry in northern Alberta, Canada. The overriding objectives of this

thesis were met by (i) testing the usefulness of the system dynamics models as an aid in decision making and (ii) evaluating the reliability of using coarser data in hydrological modeling by identifying ways for incorporating those datasets to simulate the future projected hydrological performance, especially in reconstructed watersheds.

6.2 Research Contribution

At the conceptual level, the main contribution of this thesis to the current body of knowledge is the modification of the site-specific in-house SDW and the development of a GSDW model as proposed in Chapter 2. The GSDW model is shown to be conceptually superior to the previous SDW model (i) through the addition of a canopy interception module; (ii) by taking advantage of the user-friendly media of the model for adding a variable for soil layer properties and rudimentary site descriptors, the addition of which proved to be useful in comparative studies; (iii) by adjoining a provision for interflow and runoff components to account for the effect of topography (surface slope); and (iv) by implementing a van Genuchten (1980) equation to describe the soil water characteristic curve (SWCC). Improving the simulation accuracy of a single hydrological component, (e.g., intercepted precipitation) enhanced the overall credibility of the model performance. The GSDW model proposed in this thesis can be considered a step towards developing a generic model, which will enable the investigation of different soil-vegetation alternatives and provide a comprehensive decision support tool.

The second contribution of this thesis is the validation of the previously developed probabilistic approach through its application to various natural and

reconstructed watersheds. This can improve our ability to choose the optimal reclaimed cover that is both ecologically feasible and economically viable. In this thesis, it was established that the reconstructed watersheds are expected to provide the desired moisture demands over time. In addition, this thesis:

(1) highlighted the advantages of adopting the probabilistic approach, along with the GSDW model, in generating suggestions for newly reconstructed soil watersheds based on the knowledge gained from previously existing covers (Chapter 3);

(2) demonstrated that the NARR precipitation and air temperature data could be successfully implemented in hydrological modeling (e.g., simulation of soil moisture dynamics and actual evapotranspiration flux), particularly for the study region and indeed could be useful in data-scarce regions. This thesis argued, and subsequently validated using literature, that NARR data had never been used to simulate soil moisture contents (Chapter 4); and

(3) addressed, for the first time, the impact of possible climate change on the hydrological performance of reconstructed watersheds in northern Alberta, Canada.

6.3 Possible Research Extension

Improvements in the model structure, approaches, and applications developed or adopted in this thesis are possible and essential. The following are possible future extensions of the research work.

- In this study, canopy was assumed to be static, ignoring the dynamic transformation to the vegetation that may occur due to vegetation

growth. Accordingly, there is an opportunity to connect this type of study to other models that simulate long run vegetation dynamics.

- It would be worthwhile to investigate the possibility of a hybrid modeling approach that uses data-driven techniques with the ability to arrive at an explicit model structure for specific hydrological processes (e.g., genetic programming equation for AET and interflow). One could then assimilate such explicit models (equations) in mechanistic models (e.g., system dynamics) and thereby improve the accuracy and reliability of the developed models.
- The relative merits of adopting an automatic calibration technique could assist in estimating and optimizing the GSDW model parameters. Moreover, a methodology to account for the effect of the model structure uncertainty needs to be investigated and adopted. More analysis regarding the predictive uncertainty propagation through a hydrological system needs to be undertaken.
- The methodology for developing maximum annual moisture deficit frequency curves could be expressed as a function of unit depth of a special type of soil cover that could be used in combination with other reconstructed covers having the same texture and different depth.

6.4 Study Limitations

Several limitations can be noted with regard to the assumptions and analysis adopted in this thesis. Two mature natural watersheds were benchmarked to relocate their canopy to existing reconstructed watersheds and to assimilate the effect of mature canopy on soil moisture patterns. This simplification ignores the effect of rudimentary site descriptors, soil stratification, and landscape topography on the simulated soil moisture, and consequently on maximum annual moisture deficit patterns. The current study pinpoints the need to conduct further comparative studies that link the performance of reconstructed and natural watersheds and build a data bank for newly reconstructed sites.

Soil moisture measurements during the winter season were not reliable due to the insensitivity of the time-domain reflectometry (TDR) sensor measurements in frozen soil. On a related note, depth-averaged point soil moisture observations cannot be considered a completely accurate depiction with respect to simulating processes in a highly complex system. Also, the GSDW model does not account for macropores, which may play an important role for soil water fluxes, especially during snowmelt period. A set of canopy interception losses observations would have added credibility to the evaluation of the model performance. Overall, the conclusions drawn from this thesis provide many opportunities for further research of various aspects of the study.

Appendix. A

A.1 Natural watersheds

Canada's boreal forest is globally significant, representing one-quarter of the world's remaining intact forests (Lee et al., 2003). In addition to the ecosystem services it provides, such as water cleansing, storing carbon and releasing oxygen, it is also home to a wide variety of wildlife. However, the boreal forest's carbon budget and its governing processes are poorly understood, especially with respect to climatic variability and change. The Boreal Ecosystem- Atmosphere Study (BOREAS) was implemented to evaluate the boreal forest's contribution to the global carbon budget and to clarify its role in the global climate system. A continuing time series of forest climate and surface radiation was needed to validate and improve large-scale climate and forecast models above the boreal forest.

The BOREAS/BERMS study area is located in Central Saskatchewan (Fig. A.1). The terrain of this area is generally flat to gently rolling, with mean elevation of 520 m. The vegetation cover is predominantly coniferous, with low species diversity. Understory vegetation is generally composed of sparse shrubs with extensive moss and lichen cover. Temperatures ranged from a maximum of 35 °C in the summer to a minimum of -40 °C in the winter. Precipitation events in the summer ranged from trace amounts to approximately 35 mm. The average maximum snow depth for the region is between 50

and 70cm (Gray, 1981). For further details on vegetation and soil conditions, see Balland et al. (2006).

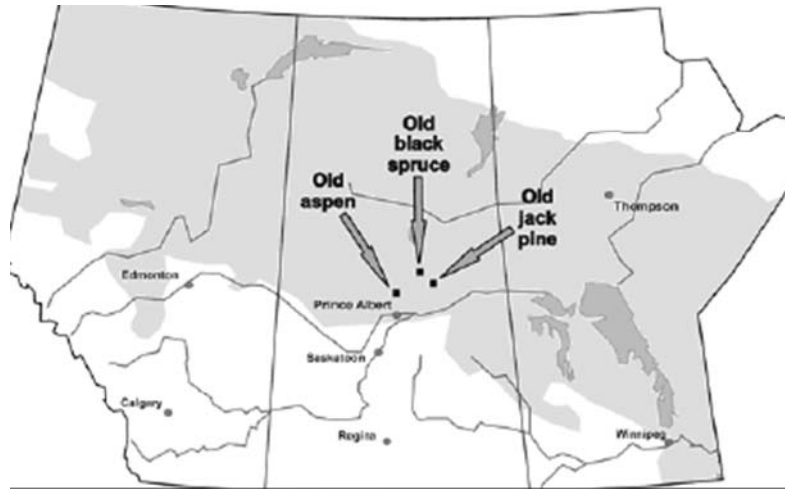


Figure A.1 Location of the study sites (old jack pine, and old aspen), Saskatchewan.

The main purpose of the installed meteorological station was to gather enough information about precipitation, temperature and other meteorological data (e.g., air temperature, humidity, radiation and wind) to fully understand the climate of the boreal forest. Most of the meteorological instruments were installed on double scaffold towers (Figure A.2).

Precipitation sensors were accompanied by wind and air temperature instruments installed on wooden platforms approximately 2-3 m high, 1 m wide and 2 m long. Soil temperature, soil moisture, soil heat flux, water table height were also measured. Description of old jack pine (OJP) and old aspen (OA) sites and description of the climate variables are presented in Table A.1 and Table A.2. Figure A.3 shows

photographs of below and above forest canopy and a schematic sketch showing soil layer stratification of the OA and OJP sites.



Figure A.2 Photographs of double scaffold tower and hut at OA (left), and forest floor at bottom of tower at OJP site (right), during summer.

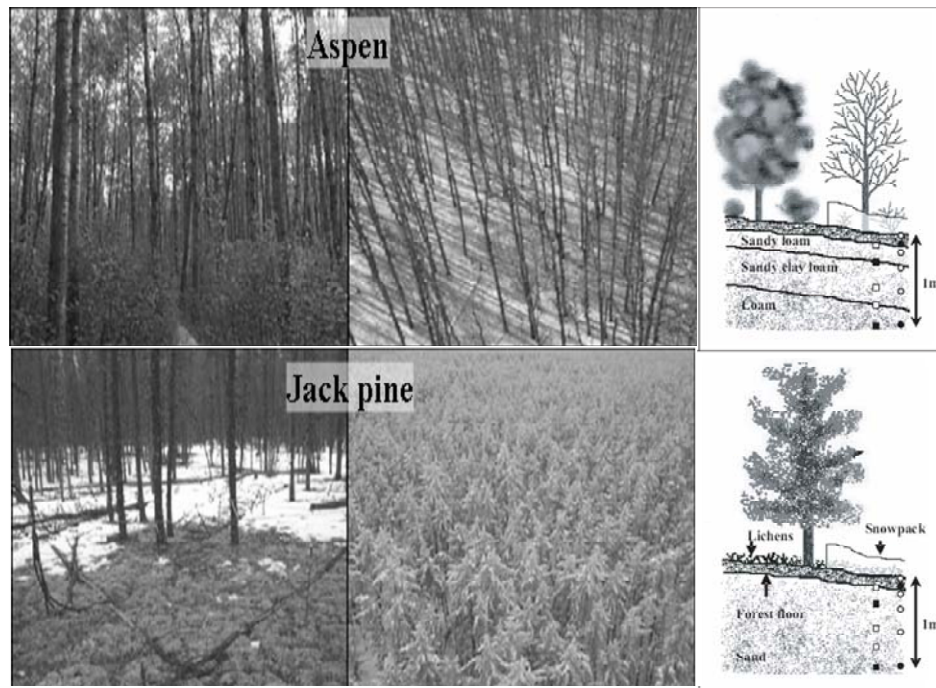


Figure A.3 Photographs of below (left), above (right) forest canopy conditions and a sketch showing soil layer stratification of the old aspen (top), and old jack pine (bottom) sites (Modified from Balland et al., 2006).

Table A.1 Description of the study sites (old jack pine, and old aspen), Saskatchewan, Canada.

	Old Aspen Site (OA)	Old Jack Pine Site (OJP)
Location	South end of Prince Albert National Park (53.629° N, -106.2° W; elevation: 600.63m).	Near Narrow Hills Provincial Park (53.875° N, -104.65° W; elevation: 579.27m).
Topography	Undulating.	Undulating.
Predominant vegetation	<p>- Hazel: canopy height varied between 1 and 3m. This bushy species grew densely enough to make walking through it difficult. While the predominant bushy species in this lower canopy was hazel, wild rose bushes, willow, and alder also grow in the area.</p> <p>- Aspen: canopy height was approximately 21m and trees were spaced between 1-5m apart (BOREAS Experiment plan; EXPLAN-94). Most of the leaves grew on the top 20% of the trees. The predominant tall tree species was “<i>white poplar</i>”, but the odd “<i>black poplar</i>” and birch grew in the OA vicinity.</p>	- Jack pine : 12-15m tall jack pine trees with alder, bearberry, moss and lichen as ground cover.
Soil Properties	1-7cm was organic (leaf litter, etc), between 7-30cm, the soil was a clay and sand till. Below 30cm, the soil became a more gravelly till, with larger rocks and more clay (Fig. A.2).	Sandy soil with very good drainage. The organic layer is 10-15cm deep (Fig. A.2).

Table A.2 Climate variables measured in the natural watersheds.

Climate variables	Description
Air temperature	Measured as °C at various heights in relation to the structure of the forest canopy.
Humidity	Measured as relative humidity at various heights in relation to the structure of the forest canopy.
Precipitation	Snow depth, precipitation accumulation, rain events measured in mm.
Wind direction	Measured in compass degrees above the forest canopy.
Wind speed	Measured in m/s above and within the forest canopy.
Atmospheric pressure	Surface pressure measured in millibars (or Pascals).
Soil temperature	Measured in °C at various depths in relation to ground level.
Soil moisture	Volumetric water content measured at various depths in relation to ground level.
Radiation	Measured in watts/m ² Includes: net radiation, downwelling shortwave, upwelling shortwave, downwelling longwave, upwelling longwave, diffuse shortwave radiation, global solar radiation and photosynthetically active radiation.
Ground heat flux	Measured in watts/m ² or °C in at least two locations per site.
Water table height	Measured in mm.
Leaf Area Index	Measured at various times of the year.

A.2.1 Equipments and limitations

a) Equipments

An accurate set of precipitation measurements is necessary for a proper simulation of the water balance. As a result, several techniques were used to measure

precipitation in the natural watersheds (e.g., Belfort models 5915 & 3000 weighing gauges, and tipping bucket rain gauge (Model 525M)). Belfort precipitation model (series 5915) is a weighing-type gauge in which a weighing mechanism converts the weight of the rainfall caught by a bucket into a resistance (BIC, 1986). Belfort 5915 model was calibrated by meteorological service of Canada (MSC), a branch of Environment Canada, in controlled lab conditions prior to deployment in field or when measurements were suspect. Both Belfort models (5915 and 3000) are sensitive to a single precipitation event of 0.254 mm and 0.6 mm, respectively. The tipping Bucket gauge (525M) is a smaller adaptation of the standard Weather Bureau Tipping Bucket Rain Gauge. It measures rainfall at rates up to 0.254 mm per hour with an accuracy of $\pm 1\%$. Output is a switch closure for each bucket tip. A tip occurs with each 0.1mm of rain with an accuracy of 1% at 0.254 mm per hour or less (CSI, 1996). Snow depth was measured using ultrasonic depth gauge (UDG01). The UDG01 operates by sending out an ultrasonic pulse and determines the time for the echo to return with an accuracy range of $\pm 1\text{cm}$ or 0.4% of Distance to the Target, whichever is greatest (CSI, 1992).

Soil moisture values during the monitoring program were measured using Campbell Scientific (CS615) and ESI Environmental Time Domain Reflectometry (TDR) Probes (CSI, 1996). CS615 consists of two stainless steel rods connected to a printed circuit board. A shielded four-conductor cable is connected to the circuit board to supply power, enable the probe, and monitor the pulse output. The accuracy of the CS615 depends on soil texture and mineral composition. ESI Environmental (TDR) measures the propagation time of a signal as it travels through a transmission line (a probe) embedded in the soil. The longer the propagation time signifies higher moisture content.

Propagation times, together with the probe length, soil and probe coefficients, can be converted directly into volumetric moisture content.

Several techniques were used to measure temperature and humidity, e.g., HMP35CF Temperature/Humidity Probe, Chromel-Constantan Fine-wire Thermocouples, Copper-Constantan Thermocouples, 107 Temperature Probe, and Platinum resistance thermometer. Temperature has been subject to tests, in which three or more instruments were compared to each other. Temperature accuracy was $\pm 0.4^{\circ}\text{C}$ over the range of -53°C to $+48^{\circ}\text{C}$ (overall accuracy is better than $\pm 0.2^{\circ}\text{C}$), whereas, RH accuracy was $\pm 1\%$ against factory references at 20°C , and $\pm 3\%$ against field references (CSI, 1992).

Three devices were used to measure radiation flux: 1) The Middleton CN1-R (CSD, 1995) was used to measure net total radiation flux (e.g., solar, terrestrial, and atmospheric); 2) Kipp & Zonen CM11 Pyranometer (Shortwave) was used to measure the irradiance (radiant-flux, Watts/m^2) on a plane surface, which results from the direct solar radiation and from the diffuse radiation incident from the hemisphere above; and 3) Middleton CN3 Heat Flux Plate was used to directly measure the conductive heat transmission in the medium in which the sensor is embedded.

b) Data Limitations

This section presents some of the problems and limitations associated with data acquisition and actions taken to solve those problems. There were some intermittently bad and/or missing temperature and relative humidity (RH) data due to poor wiring or

due to data downloads via modem at OA site. The Belfort 3000, at the OA site, was “sticking” due to a broken spring, which was not discovered until it was removed in December, 1999. Also, the volumetric water content data accuracy was questionable between Nov. 1996 and Oct. 1998 for two reasons:

1. Old model sensors, without lightning protection were a likely cause of bad and/or missing data during this period.
2. Old Aspen soils high clay content below 30 cm.

As a result, calibration/validation years for the GSDW model were selected in 1999 and 2000 to skip the malfunction period.

For the OJP site, the tipping bucket sensor measured only ~7% of Belfort precipitation from May 7 to July 9, 1998 due to a programming error and values were set to missing in the quality control data files (AL1). Also, the cup wheels on the anemometer at the Belfort rain gauge sometimes froze up during the winter and the wind speed at the Belfort was negative at the start. This problem was detected when the wind speed stayed at 0 for days at a time. Those errors were fixed in the AL1 file. Some sensors were not working properly for a while (e.g., wind speed at Belfort 3000, air temperature at Snow Depth sensor and surface pressure). The surface pressure data were replaced with data from University of British Columbia's pressure sensor.

A.2 Reconstructed Watersheds

The mining process results in a large disturbance of ecological functions of nature such as the hosting of aquatic ecosystems and vegetation biomes. The United Nations Environment Program has identified Alberta's oil sands mining projects as one of 100 key global "hotspots" of environmental degradation (UNEP, 2006). Syncrude Canada Ltd. (SCL) has been conducting large scale experiments on its reconstructed watersheds. One such reconstructed landform is the South Hills dump. It was constructed in stages with shale overburden from mining between 1980 and 1996. South Bison Hills (SBH) is a flat reclamation landform located adjacent to the D-covers with an approximate area 2 km², and rising 60 m above the surrounding landscape. The top and the inclined slopes (D-cover sub-watersheds) were capped with a peat mineral mix (15-20 cm thick) overlying a secondary (glacial till) layer (20-80 cm thick). Figure (A.4) shows the location of the reconstructed study areas in Fort McMurray, Alberta, Canada. The area was fertilized and seeded to agronomic barley in the summer of 2002 and then planted to white spruce and aspen in the summer/fall of 2004 (Carey and Duncan, 2004; Parasuraman et al., 2007).

The South West Sand Storage (SWSS) site is located at Mildred Lake mine approximately 40 km north of Fort McMurray, Alberta, Canada (Fig. A.4). The SWSS facility is the largest operational tailings dam in the world, covers an area of about 23 km² and elevated 40 m higher than the surrounding landscape (Parasuraman et al., 2007). The construction of the SWSS facility began in early 1990's and was later curtailed with

a 45 cm Till/secondary soil layer between 1995 and 1998 (Chaikowsky, 2003), subsequently seeded with vegetation in 2001 (Figure A.5).

The reconstructed study area is located in the semi-arid region where potential evaporation exceeds precipitation. Based on the climate data from an Environment Canada meteorological station at Fort McMurray (56° 39' N, 111° 13.2' W), a 30-year period (1971-2000) mean annual temperature was 0.7 °C, and the annual precipitation was 455.5 mm, of which 342 mm occurs as rainfall.

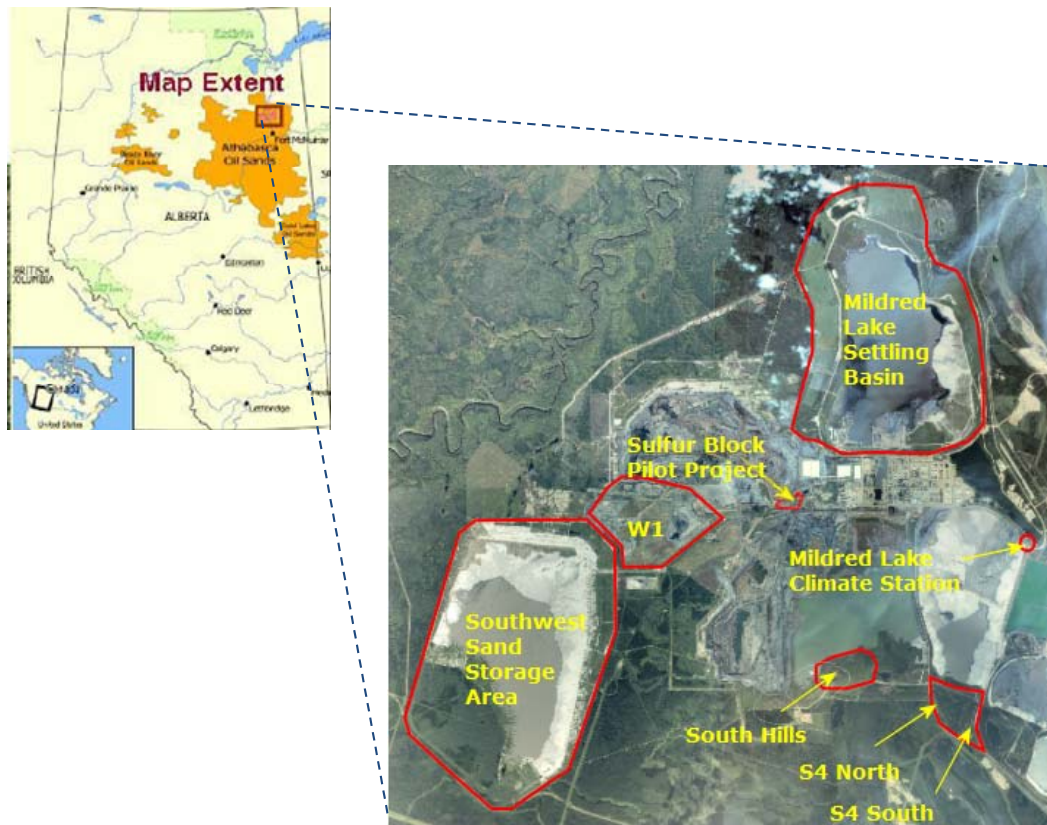


Figure A.4 Location of the reconstructed study areas (SWSS and South Hills).



Figure A.5 SWSS cross section comprise of 45 cm of till (dark) over 100 cm tailing sand
(After Izadifar, 2006).

A.2.1 Equipments and limitations

a) Equipments

A for the study areas, fully automated meteorological stations were installed to monitor climate variables (e.g., air temperature, relative humidity, wind speed and direction, net radiation, and precipitation). The 107F temperature probe and HMP45C temperature and relative humidity probe, both housed in radiation shields, were mounted at 2.1m and 1.8m, respectively. The TE525WS tipping bucket rain gauge and the CS705 snowfall conversion adapter were mounted on a steel stake approximately 4 m from the weather station. The CS705 was placed on top of the tipping bucket with an orifice elevated at 1.1 m, surrounded by an alter wind shield to reduce the wind effect on precipitation catch. The reservoir on the CS705 was filled to the overfull mark with

regular motor antifreeze and topped off with a thin layer of baby oil to prevent the antifreeze from evaporating. A catch pail was placed under the tipping bucket to retain the antifreeze as the snowfall displaces it. Each April the snowfall adapter must be removed and the tipping bucket is replaced to its original height. A 10 m grid was staked out over the prototype covers measuring snow depths, and snow pack densities were measured using a standard fibber glass snow corer and scale (Boese, 2003). A RM Young (Model 05103) wind monitor was mounted 3 m form the ground on a steel cross arm (RM. Y. Co., 1980; 1990)

An automated Bowen ratio monitoring system, installed in June 1999 and decommissioned in October 2008, moved between the Prototype D-covers and Bill's Lake during the summer months, and data was output every 30 minutes. Soil heat flux was measured using four TCAV soil thermocouples, two HFT3 heat flux plates and a CS615 TDR water content sensor (CSI, 1998). Down and up-welling long and short-wave radiation was measured using a Kipp and Zonen CNR-1 net radiometer mounted 3.1 m above the ground. Measurements of the latent heat fluxes were made with the eddy covariance technique (EC) and reported with 30-min interval. LAI was measured near the flux tower using a plant canopy analyzer (PCA) (model LAI-2000).

Thermocouple sensors recorded soil temperature every 30-min, whereas, CS615 soil moisture sensors (TDR) were used to measure the volumetric moisture content of the soil at different depths below the ground surface.

b) Data corrections and limitations

Typically, eddy covariance underestimates turbulent fluxes, sensible heat (H) and latent heat ($\lambda_v E$), resulting in a residual flux density. This underestimation is commonly endorsed to high and low frequency eddies that are not measured at the sampling frequency (10 Hz) (Finnigan et al., 2003). Carey (2008) calculated the slope of the relationship between net radiation minus ground heat flux ($R_n - G$) and the total turbulent flux ($H + \lambda_v E$). The slope indicated that eddy covariance underestimates turbulent fluxes by 17 % for all measurement periods; accordingly, H and $\lambda_v E$ values were corrected by adjusting energy balance closure. Additional corrections to the flux measurements were done by Carey (2008): 1) fluxes were removed when the friction velocity as measured by eddy covariance was less than 0.1 m s^{-1} or/and during periods of rainfall; and 2) flux data were removed when rapid and unexpected changes in state variables occurred over half-hour intervals using a criteria of 1.5 standard deviation from the mean value for that time period. Short half-hour breaks were filled by linear interpolation, whereas, for longer breaks, turbulent fluxes were estimated using the mean diurnal variation method by replacing missing observations by the mean for that time period based on previous and subsequent 7 day periods (Carey, 2008).

Routine maintenance of the Bowen ratio monitoring equipment was necessary in order to ensure the collection of accurate measurements. Every two weeks, the air intakes filters had to be changed and the level of the net radiometer had to be checked and adjusted frequently. The mirror in the hygrometer and the fine wire thermocouples were routinely cleaned.

Table A.3 Description of the reconstructed study sites.

	D-covers	SBH	SWSS
Location	North of Fort McMurray (57°39'N, 111°13'W), northern Alberta, Canada.		
Topography	5H:1V	Undulating.	20H:1V
Predominant vegetation	Barley nurse crop (<i>Hordeum Jubatum</i>), and tree seedlings of white spruce (<i>Picea glauca</i>) and aspen (<i>Populus tremuloides</i>).	Foxtail barley (<i>Hordeum Jubatum</i>), and fireweed (<i>Epilobium angustifolium</i>).	Ground cover vegetation including horsetail (<i>Equisetum arvense</i>), fireweed (<i>Epilobium angustifolia</i>), and white and yellow clover (<i>Melilotus alba</i> , <i>Melilotus officinalis</i>). Tree species include Siberian larch (<i>Larix siberica</i>), hybrid poplar (<i>Populus sp. hybrid</i>), trembling aspen (<i>Populus tremuloides</i>), white spruce (<i>Picea glauca</i>) and willow.
Soil Properties	The three covers were constructed with a thickness of 0.5 m, 0.35 m, and 1.0 m comprised of 0.2 m, 0.15 m, and 0.2 m of peat/mineral mix overlying 0.3 m, 0.2 m, and 0.8 m thickness of glacial till, respectively, overlying shale.	0.2 m of peat/mineral mix overlying 0.8 m of glacial till, overlying saline sodic shale.	0.2-0.4 m of Till/secondary cover material over 1.0 m of tailings sands.

A.3 References:

- Balland, V., J. Bhatti, R. Errington, M. Castonguay and P. A. ARP, 2006. Modeling snowpack and soil temperature and moisture conditions in a jack pine, black spruce and aspen forest stand in central Saskatchewan (BOREAS SSA). *Canadian Journal of Soil Science*. 86:203-217.
- Belfort Instrument Company. 1986. Instruction Manual Catalog Number 5-780 Series Universal Recording Rain Gage, *Instruction Manual number 8777*.
- Boese, K., 2003. The design and installation of a field instrumentation program for the evaluation of soil-atmosphere water fluxes in a vegetated cover over saline/sodic shale overburden, *MSc Thesis*, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, 169 pp.
- Campbell Scientific. 1992. Model HMP35CF Temperature and Relative Humidity Probe Instruction Manual.
- Campbell Scientific. 1992. UDG01 Ultrasonic Depth Gauge Operator's Manual. Campbell Scientific Canada Corp.
- Campbell Scientific. 1996. CS615 Water Content Reflectometer Instruction Manual. Campbell Scientific Inc.
- Carey, S. K., and Duncan, B. S. (2004), Evaporation from Waste-Rock and Restoration Surfaces: A Comparative Analysis. Proceedings of the Water and Environment Specialty Conference of the Canadian Society for Civil Engineering, Saskatoon, SK, Canada.

- Carey, S.K., 2008. Growing season energy and water exchange from an oil sands overburden reclamation soil cover, Fort McMurray, Alberta, Canada, *Hydrological Processes*, 22:2847–2857.
- Carter-Scott Design. May 1995. Instruction Manual for Middleton CN1-R Net Pyrradiometer Edition: CN1R-v1.1.
- Chaikowsky, C.L.A. 2003. Soil moisture regime and salinity on a tailing sand storage facility. *M.Sc. Thesis*, University of Alberta, Edmonton, Alberta, Canada.
- Finnigan JJ, R. Clement, Y. Mahli, R. Leuning, and HA. Cleugh 2003. A re-evaluation of long term flux measurement techniques part I: Averaging and coordinate rotation. *Boundary, Layer Meteorology*, 107: 1-48.
- Gray, D.M. 1981. Handbook of Snow. Toronto, ON: Pergamon.
- Izadifar, Z., 2010. Modeling and analysis of actual evapotranspiration using data driven and wavelet techniques. *MSc thesis*, Dept. of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, SK, Canada.
- Lee, P., D. Aksenov, L. Laestadius, R. Nogueron and W. Smith, 2003. Canada's Large Intact Forest Landscapes. *Global Forest Watch Canada*, Edmonton, Alberta. 84 pp.
- Parasuraman, K., A. Elshorbagy and S.K. Carey, 2007. Modelling the dynamics of the evapotranspiration process using genetic programming, *Hydrological Sciences Journal*, 52(3):563–578.
- R.M. Young Company. 1980. Instructions, Gill Microvane 3 Cup Anemometer. R.M. Young Co.
- R.M. Young Company. 1990. Wind Monitor High Resolution Wind Sensor information sheet. R.M. Young Co.

United Nations Environment Programme (UNEP), 2006. Flying around the globe on a time machine.

(<http://www.unep.org/Documents.Multilingual/Default.asp?DocumentID=487&ArticleID=5350&l=en>)

A.4 Reconstructed watersheds photos



Figure A.6 Oil sands mining operation at Mildred Lake Area, Fort McMurray, Alberta
(After Izadifar, 2010).



Figure A.7 SWSS site Eddy Covariance (EC) Tower in 2007.



Figure A.8 Sample of the existing vegetation at SWSS site (Summer 2009).



Figure A.9 Sample of the existing vegetation at SBH site (summer 2009).



Figure A.10 Sample of the existing vegetation at D3 cover (summer 2009).